EFFECT OF MIX PARAMETERS ON PERFORMANCE AND DESIGN OF COLD MIX ASPHALT

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Thesis

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CERTIFICATE

This is to certify that the project thesis entitled "**Effect of Mix Parameters on Performance and Design of Cold Mix Asphalt**" submitted by **Swayam Siddha Dash** bearing roll no. 211CE3241 in partial fulfillment of the requirements for the award of **Master of Technology** in **Civil Engineering** with specialization in **Transportation Engineering** during 2011-2013 session at the National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance. To the best of my knowledge, the results contained in this thesis have not been submitted to any other University/Institute for the award of any degree/diploma.

Date:

Place: Rourkela

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ABSTRACT

Hot mix technology has seen significant advances through many research programs. Cold mix technology is lagging behind in both research and application fields which is quite observable in a developing country like India. This is the primary motivation underlying selection of this cold mix technology as the present research area. Besides, it has environmental and economical advantages over hot mixes. Till now there is no universally accepted cold mix design procedure. In the absence of uniformity in the laboratory cold mix design procedures followed by different researchers/agencies/organisation, it is difficult to form reliable correlations and to have a comparative study between experimental results reported by them. Hence the objectives of this project work are aimed to select important mix parameters and determine their effects on performance of Cold Mix Asphalt (CMA). The mix parameters selected for the present work are (i) method of compaction, (ii) level of compaction, (iii) additives and (iv) aggregate gradation. The first three parameters are selected for their importance as presented in a number of previous research works. The last one has been selected as nowhere in literature much attention has been paid to the aggregate gradation which is the skeleton of the compacted mix. It is observed that Bailey method for gradation selection is the only method for HMA/SMA mixture which analyses the aggregate gradations both considering the blend by volume as well as blend by weight. In this study Bailey's concept has been considered for cold mix design. All the mix parameters have been selected to assess the effect on Marshall properties of CMA mixture. Initially a suitable experimental methodology has been prepared and then the effects of selected mix parameters on performance of compacted mix are studied. Finally a comparative study for above results has been done on basis of the Marshall Stability and air void content of the cold mix. Considering all the selected mix parameters it is observed that only in case of gyratory compaction the adequate air void range (3 to 5 %) in cold mixes can be achieved. Besides, though each and every parameter has contributed to increase the Marshall Stability of cold mixes, cement and developed gradations have shown more significant increase in stability of cold mixes.

Keywords : Cold mix compaction, Additives, Bailey concept, Aggregate gradation, Cold mix design.

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LIST OF ABBREVIATIONS

AI MS-14	Asphalt Institute Manual Series - 14
BC	Bituminous Concrete
CBEM	Cold Bituminous Emulsion Mixture
CMA	Cold Mix Asphalt
CMS	Cationic Medium Setting
CRRI	Central Road Research Institute
CUW	Chosen Unit Weight
IEC	Initial Emulsion Content
IRAC	Initial Residual Asphalt Content
MORTH	Ministry of Road Transport and Highways
NMAS	Nominal Maximum Aggregate Size
OPWC	Optimum Pre-wetting Water Content
ORAC	Optimum Residual Asphalt Content
OTLC	Optimum Total Liquid Content
PCS	Primary Control Sieve
PWC	Pre-wetting water content
RAC	Residual Asphalt Conten
SCS	Secondary Control Sieve
SMA	Stone Matrix Asphalt
TCS	Tertiary Control Sieve
VA	Air Void
VMA	Voids in Mineral Aggregate

Chapter 1

Introduction

1.1 Overview

Several ambitious road construction plans and activities primarily involve bituminous pavements with hot mix technology. Hot mix technology which is a very conventional method for road construction, has structurally satisfied the performance requirements over many years. The procedures generally followed by the hot mix technology are : heating of binder and aggregate, mixing, tack coating, laying of mix followed by the compaction process everything done at high temperature in a range of 120ºC to 165ºC temperature. Though performance wise this has been the most suitable for pavement structures, but their high use have several drawbacks like environmental degradation, high energy consumption, increase in carbon footprint, low output for mix production, low laying work in rains and cold weather, limited construction period in a year, oxidative hardening of binder, health and safety hazard to labour (Pundhir et al., 2012). Besides this, in some North and North Eastern parts of India like Jammu and Kashmir, Assam, Manipur, Meghalaya, Arunachal Pradesh and others, rural road projects involving several lakhs and crores of rupees are beyond time. Due to topographical and weather constraints, it is difficult to work with hot mix technology in such hilly regions, heavy rainfall and forest zones. So, it is desirable to find out a suitable alternative for hot mix technology.

In the emulsion based cold mix technology, the addition of pre-wetting water to the aggregate, thereafter addition of emulsion to it, production of the mix, laying and compaction, all processes are done at the room temperature (23ºC to 25ºC). In addition to this, field trials have proved that cold mix can be easily produced by using hot mix plant and laid in using similar techniques. It is also a labour friendly technology.

Uemura and Nakamori (1993) conducted both laboratory and field studies on cold mixes and concluded that cold mixes were more environmental due to elimination of dust and gaseous emissions as the aggregate and emulsified asphalt did not have to be dried for use in mixture. They also found the performance of cold mixes in an acceptable level.

Dittmar (2011) observed that cracks formed in cold mix asphalt pavement repaired themselves over time. He also recommended that because of this flexibility of cold mix surface it could last longer on low volume roads than hot mix.

Needham (1996) suggested the production of cold mix for a range of different applicational purposes. Cold mix can be used mainly for base course and sometimes for binder or wearing course. Cold mix can be applied through a number of methods ranging from hand application through graders, finishers or pavers to self contained mixing and laying plants. Oke (2010) suggested that among varied compaction methods in field, the preferred method seems to be steel rolling, followed by very heavy pneumatic tyred roller and finally finishing with steel rolling.

Many researchers (Needham 1996, Ibrahim 1998, Thanaya 2003, Thom 2008) in this field had recommended cold mix asphalt to be much more efficient than hot mix asphalt in terms of energy savings. Besides this, Zoorob and Thanaya (2002) recommended cold mix asphalt mixtures to be more universally accepted for low to medium traffic conditions, for works in remote areas and for small scale jobs such as reinstatement work and footways.

1.2 Statement of the Problem

Though the emulsion based cold mixes overcome hot mix problems, they have attracted little attention and considered inferior to hot mix as structural layers due to their less satisfactory performance. Thanaya et al. (2009) reported some major problems with cold mixes such as high air-void content in the compacted mixes, weak early life strength due to pre-wetting water, long time required to achieve fully cured samples for maximum performance. In addition to this the pre-wetting water in cold mix which is considered as an important part of the process, becomes a problem since inhibiting compaction. Various researches have been carried out to improve the properties of cold mix till now. But still they are very few in comparison to the same in case of hot mix.

Several additives, chemicals and fibers were tried to modify the cold mix properties. Most of the research works recommended addition of cement as it improved the mix properties showing highly satisfactory performances. But cement emits heavy amount of CO_2. China (2005) estimated the emission of CO_2 as 0.815 ton per 1 ton of cement production whereas according to Hong Kong Concrete Institute the emission was 0.6 to 1 ton of CO_2 per 1 ton of cement production. Besides it, cement is also a costly material.

In another study on cold mix carried out by Brown and Needham (2000), they found that mechanical properties of the mixes were affected by a number of parameters, including binder grade, void content, curing condition, curing time, and additives such as cement. The laboratory procedures followed by different researchers was varied in terms of curing and other parameters for evaluation of suitable mechanical properties. Hence, no universally accepted cold mix design method is available till now.

The Ministry of Road Transport and Highways (MORTH 2001) specification introduced the cold mix design procedure which simply followed the Asphalt Institute Manual Series-14 (1997). While MS-14 did not specify any required air void range, MORTH provided the adequate air void range as 3 to 5 % at 50 blows of compaction level. But Thanaya (2007) showed that achieving 5 to 10 % air void was difficult even at 75 blows of compaction level. Also Pundhir (CRRI, New Delhi) reported a range of 7 to 8 % air voids achieved for the cold mix and he also observed the field performance of cold mix in a satisfactory level. Hence, 3 to 5 % air void range provided by MORTH seems to be an ideal one, but its feasibility should be proved.

1.3 Objectives and Scope

The broad research objectives of the study are described below.

- To select mix parameters and evaluate their effects on properties of cold mix asphalt (CMA) mixtures.
- To study and analyse the effects of aggregate gradation on properties of CMA mixtures.
- To recommend some most desired mix parameters for consideration in cold mix design from performance point of view.

The overall framework of the present study is illustrated through the block diagram in figure 1.1.

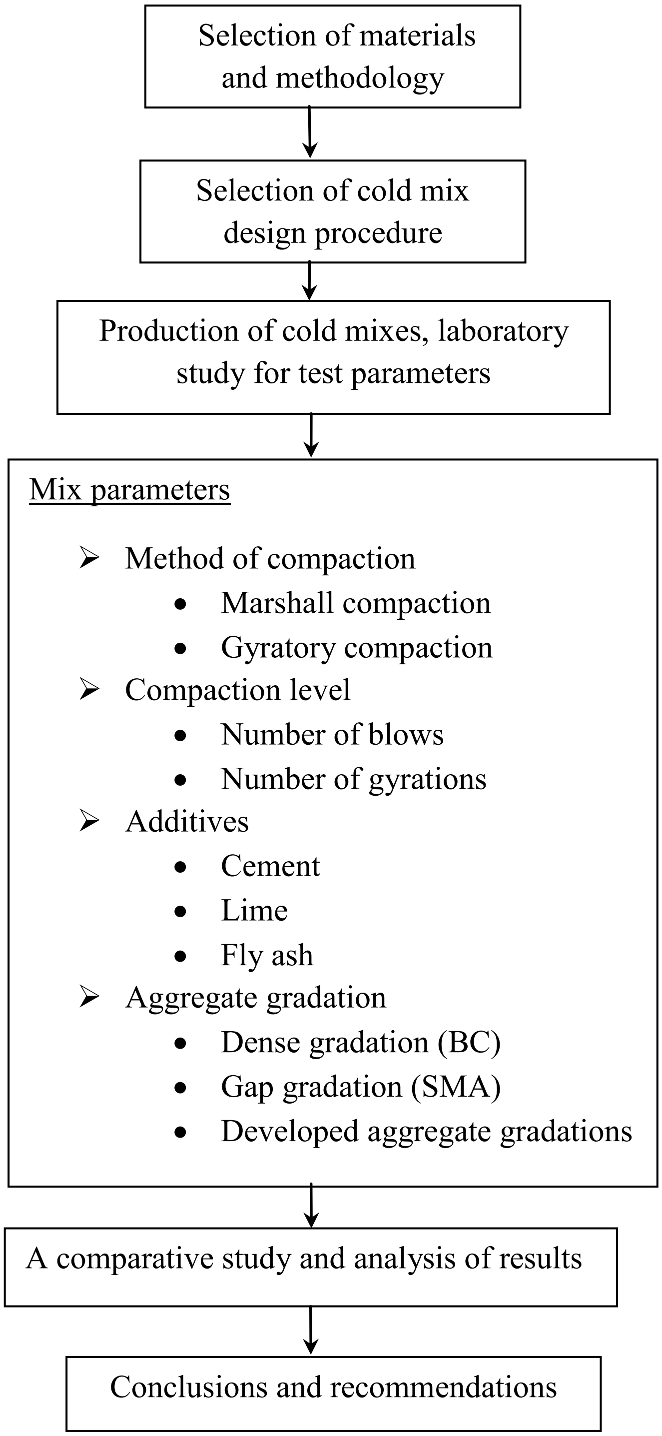

Figure 1.1 Overall framework of the study

The mix parameters selected for the present work are method and level of compaction, additives and aggregate gradation. The first three parameters are selected for their importance as presented in a number of previous research works and the last one is selected as nowhere in literature much attention has been paid to the aggregate gradation which is the skeleton of the compacted mix.

1.4 Justification and Relevance of Study

The science of bitumen emulsion based cold mix technology should be the focus of significant research and development efforts so that it can advance the cold mix applications, their specifications and test methods. Hot mix technology has seen significant advances through many research programs. Cold mix technology is lagging behind in both research and application fields which is quite observable in a developing country like India. This is the primary motivation underlying selection of this cold mix technology as the present research area.

For the lack of uniformity in the laboratory cold mix design procedures by different researchers, it is difficult to form reliable correlations and to have a comparative study between experimental results reported by them. The primary and tertiary objectives of this research work are aimed to solve these difficulties.

For CMA mixtures design, nowhere in literature much attention has been paid to the aggregate gradation which is the skeleton of the compacted mix. Based on this, the secondary objective of the research work is set to study the influence of aggregate gradation on properties of cold mix.

1.5 Thesis Organisation

This report consists of five chapters as they are described below.

- The first chapter introduces an overview for this research area and describes the objectives and scope of this study. It also provides the justifications for the study.
- The second chapter gives a thorough discussion on various literatures in cold mix asphalt area related to bitumen emulsion, mix design and various additives.
- In third chapter methodology of experimental investigations for this project work is highlighted. Information regarding the collected materials, adopted mix design and laboratory test procedure are provided in detail.
- The results and analysis are illustrated in chapter four.
- The fifth chapter provides the summery of the project work and conclusions of the study. It also gives limitations of present study and recommendations for the future research work.

References are given at the end of this report.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, extensive literature survey on the various laboratory studies conducted for cold mix asphalt has been discussed. While going through the literature review, few works were observed in this field in comparison to hot mix asphalt.

2.2 Use of Bitumen Emulsion in Cold Mix Asphalt

Transportation research circular entitled “Asphalt Emulsion Technology” (TRB, 2006) has provided detailed information regarding bitumen emulsion. An emulsion is a dispersion of small droplets of one liquid in another liquid. Emulsions can be formed by any two immiscible liquids, but in most emulsions one of the phases is water. Bitumen emulsion is a liquid product in which a substantial amount of bitumen is suspended in a finely divided form in water in presence of emulsifiers. The bitumen droplets range from 0.1 to 20 micron in diameter. Standard bitumen emulsions is a brown liquid and contain 40% to 75% bitumen, 0.1% to 2.5% emulsifier, 25% to 60% water plus some minor components.

Classification and nomenclature of bitumen emulsion: The type of emulsifying agent used in the bituminous emulsion determines whether the emulsion will be anionic or cationic. Cationic emulsions have bituminous droplets which carry a positive charge. Anionic emulsions have negatively charged bituminous droplets. Based on their setting rate, which indicates how quickly the water separates from the emulsion, both anionic and cationic emulsions are further classified into rapid setting (RS), medium setting (MS), and slow setting (SS). The setting rate is basically controlled by the type and amount of the emulsifying agent. The principal difference between anionic and cationic emulsions is that the cationic emulsion gives up water faster than the anionic emulsion. In the nomenclature of emulsions according to ASTM D977 and D2397, cationic RS, cationic MS, and cationic SS emulsions are denoted by the codes CRS, CMS, and CSS whereas anionic emulsions are called RS, MS, and SS. All are followed by numbers and text indicating the emulsion viscosity and residue properties. The numbers "1" and "2" indicates low and high viscosity respectively and the text "H" stands for hard grade asphalt cement (low penetration). For example SS-1H would be a slow-setting (i.e. low reactivity) anionic emulsion with low viscosity and a hard asphalt residue. The QS (quick-setting) and CQS (cationic quick-setting) designations for quick-setting emulsions have been introduced for emulsions intermediate in reactivity between MS and SS, which do not need to pass the cement mix test and are used primarily in quick-set slurry surfacing applications. Local authorities have many other classification schemes associated with emulsions with particular properties. Some specifications letters such as P or LM may indicate polymer-modified or latex-modified asphalt emulsion, S may indicate high solvent content and terms such as AEP (asphalt emulsion prime) and PEP (penetrating emulsion prime) and ERA (recycling agent emulsion) may indicate emulsions with specific uses.

Breaking mechanism of bitumen emulsion: Macro emulsions are inherently unstable. Over a period of time, which may be hours or years, the asphalt phase will eventually separate from the water. Asphalt is insoluble in water, and breakdown of the emulsion involves the fusion of droplets (coalescence). The asphalt droplets in the emulsion have a small charge. The source of the charge is the emulsifier, as well as ionisable components in the asphalt itself. These small charges on the droplets normally provide an electrostatic barrier to their close approach to each other (like charges repel). However when two droplets do achieve enough energy to overcome this barrier and approach closely then they adhere to each other (flocculate). Over a period of time, the water layer between droplets in a floccule will thin and the droplets will coalesce. Factors which force the droplets together such as settlement under gravity, evaporation of the water, shear or freezing will accelerate the flocculation and coalescence process.

Leech (1994) recommended the use cationic bitumen emulsion for being compatible with most aggregates. Brown and Needham (2000) indicated that emulsion droplet coalescence was affected by pressure, bitumen type, emulsifier level, cement and temperature Pouliot et al. (2003) indicated that mortars made with the cationic emulsion (CSS-1) showed higher strengths and elastic modulus than mortars made with anionic emulsion (SS-1). Song et al. (2006) purposed to evaluate the feasibility on the use of an asphalt emulsion as a polymeric admixture. They showed that water proofness, carbonation resistance and chloride-ion penetration resistance of the asphalt-modified mortars were markedly improved with the increase in the polymer cement ratio, while their compressive strength and adhesion to mortar substrates were reduced with the increase in polymer-cement ratio. Oruc et al. (2007) stated that aggregate type had effects on determination of the emulsion type which could be either cationic or anionic. The reactivity of the aggregates was depended on the proportion and distribution of negative charges. For example, acidic aggregates containing high silica (SiO2) had negative charges on surface of aggregate. These negative charges caused the adhesion bond between the aggregate and the cationic emulsion much stronger.

2.3 Cold Mix Design Method

The bituminous binders used in cold mixes are emulsified and hence in liquid form. So, it can be applied at relatively low temperatures compared to that of hot mix. Needham (1996) stated that although cold mix generally manufactured at ambient temperatures, some processes could also use the emulsion warmed to around 60°C.

Till now there is no universally accepted cold mix design method and therefore no thumb rule that can be followed. There is no general existing equipment made specifically for the design of cold mixes, hence those for hot mixtures are most frequently used. Marshall method has been popularly used to design cold mixes. Later on Marshall compaction is replaced with gyratory compaction to avoid compaction problems and to obtain improved mix properties.

Ministry of Road Transport and Highways (MORTH, 2001) specification for Road and Bridge Works (Fourth Revision) introduced the procedures for bituminous cold mix. The design guidelines were based on those of Asphalt Institute Manual Series 14 (MS 14). During the literature review it was observed that Thanaya (2007) provided some useful recommendations for the cold mix design procedure. The main difference between the procedures provided by MS 14 and Thanaya is the optimum total liquid content (OTLC) and optimum residual asphalt content (ORAC) determination process. To determine the ORAC value, MS 14 suggested to conduct both dry stability and soaked stability test at each residual asphalt content (RAC) while Thanaya suggested to conduct only soaked stability test at each RAC and to find out the dry stability value only at ORAC to determine the retained stability. Later one is more efficient and economic. But Thanaya did not consider the OTLC determination step to make the design procedure more suitable for the field (may not be suitable for laboratory). The design procedures are summarised in table 2.1. Design requirements as per MORTH is provided in table 2.2.

Table 2.1 Comparative study between MS 14 and Thanaya CMA design procedure

AI MS 14 (1997)	Thanaya (2007)
Determination of ➢ Aggregate gradation (As per specification) ➢ IRAC and IEC (As per formula) ➢ OPWC (Coating Test) ➢ OTLC (Dry Stability Test) ➢ ORAC (Dry Stability and Soaked Stability Test for each RAC)	Determination of ➢ Aggregate gradation (As per specification) ➢ IRAC and IEC (As per MS 14 formula) ➢ OPWC (Coating Test) ➢ Compaction Level to achieve porosity target (Dry Stability Test) ➢ ORAC (Soaked Stability Test) ➢ Retained Stability (Dry Stability Test), AFT (As per formula) and Ultimate strength (fully cured mix) at ORAC

Table 2.2 Design requirements for CMA mix as per MORTH

Properties	Values
Marshall Stability	2.2 kN
Minimum flow	2 mm
Air voids	3 to 5 %
Maximum stability loss	50 %
Level of compaction	50 blows
Emulsion content	7 to 10 %
Voids in mineral aggregate (VMA)	BC: 14 %, SMA: 15%

It should be noted that the VMA value for BC and SMA mix is presented according to their nominal maximum aggregate size.

All the processes are clearly elaborated in following steps given below.

a) Determination of Aggregate Gradation: This simply follows standard specifications for aggregate gradation selection.

b) Determination of Initial Residual Asphalt Content (IRAC) and the Initial Emulsion Content (IEC): Initial Residual Asphalt Content (IRAC) is calculated utilizing an empirical formula:

$$IRAC = (0.05\ A + 0.1\ B + 0.5\ C) \times (0.7) \qquad 2(i)$$

Where A is the percentage of aggregate retained on sieve 2.36 mm, B is the percentage of aggregate passing sieve 2.36 mm and retained on 0.075 mm and C is the percentage of aggregate passing 0.075 mm.

IEC is calculated using formula:

$$IEC = IRAC / [\ X\ (\text{in }\%)] \qquad 2(ii)$$

Where IEC is the Initial Emulsion Content by mass of total mixture and X is the asphalt content of the emulsion.

c) Coating Test and Determination of optimum pre-wetting water content (OPWC): Using the IEC value coating test is carried out by mixing dry aggregates and filler with varied amount of water. After the pre-wetting of aggregates the asphalt emulsion is added and then mixed for about 2 to 3 minutes until the uniform coating is obtained. The optimum pre-wetting water content (OPWC) that gives the best asphalt coating on the mineral aggregates (in which the mixture was neither too sloppy nor too stiff) is determined. The degree of coating should not be less than 50 % by visual observation.

d) Dry Stability Test and Determination of Optimum Total Liquid Content at Compaction (OTLC): Utilizing the IEC, the mix is compacted at the predetermined compaction level (50 Marshall blows on each side of the sample). The loose mixtures are compacted at OPWC and then at PWC (pre-wetting water content) with 1 % increasing steps from OPWC. The samples are kept for one day in their moulds after compaction and thereafter extruded and kept for one day in an oven at 40ºC. Then they are removed from the oven and stored at room temperature for one day. After that the samples are tested for Marshall Stability at room temperature and the results obtained are referred as dry stability. This test gives the OTLC at which the dry stability of the sample is maximum. Where OTLC is the summation of liquid content of IEC and pre-wetting water content at maximum dry stability.

e) Soaked Stability Test and Variation of Residual Asphalt Content (RAC): By maintaining a constant OTLC value, the RAC is varied in a range of 7 to 10 % emulsion content (EC) value with 0.5 % increment in RAC. Specimens are mixed, compacted at each of these RAC values. Then the same curing process is followed up to the completion of the oven curing as explained above in case of dry stability test. The dry samples are then water conditioned (capillary soaking). In this procedure half the thickness of each compacted specimen is soaked in water at room temperature for 24 hour. The specimen is then inverted and the other half is soaked for next 24 hour. The samples are subsequently towel dried and tested for Marshall Stability at room temperature. The Marshall Stability test results obtained are referred as soaked stability. At this condition the samples do not achieve full curing stage as contained some amount of water.

f) Determination of Optimum Residual Asphalt Content (ORAC): ORAC is determined by optimizing the parameters such as soaked stability, air void, flow value for soaked samples of all residual asphalt content (RAC) variation. The main parameter considered is the maximum soaked stability while all other parameters should meet the CMA design requirement as per MORTH (2001) specification at the proposed ORAC. In case either the soaked stability or the air void result is found to be inadequate, the compaction level should be increased to meet the required target.

g) Determination of Retained Stability: Retained stability is the ratio of soaked stability to dry stability. Both soaked stability and dry stability are considered at ORAC only. Maintaining the OTLC value, the dry stability of the mixture is determined at ORAC only. The maximum stability loss is 50 %, hence, the minimum retained stability is 50 % at the proposed ORAC.

2.4 Method and Level of Compaction

Thanaya et. al. (2009) concluded that when incorporating cement, the cold mix should be compacted soon after mixing to maximise the results and to avoid workability problems. If not possible, then loose mixture can be kept in a sealed container and compacted after approximately 24 hour. Brown (1992) reported 75 blows of Marshall compaction caused in significant degradation of aggregates particularly in SMA mixes.

Thanaya (2007) reported that the application of heavier compaction level to be inevitable in cold mixes as the emulsion set (the bitumen droplets of the emulsion coalesce), hence the mixes stiffen during compaction. He also tried to simulate between the Marshall and Gyratory method of compaction as follows.

(a) Medium compaction level: 80 revolutions in the gyratory compactor, which is equivalent to the compaction effort generated when applying 50 blows to each end of the sample using a Marshall hammer.

(b) Heavy compaction level: 120 revolutions in the gyratory compactor, which is equivalent to the compaction effort generated when applying 75 blows to each end of the sample using a Marshall hammer.

In another research by Mike Hemsley Jnr (2002) the concept of locking point was applied. In this method samples with different asphalt contents were first compacted to 200 gyrations, representing maximum possible density after trafficking. Then the curve of height verses gyrations was examined and the locking point determined. As the height of the specimen was decreased by each gyration, there a point reached where aggregate to aggregate contact was prevented further consolidation and the height did not decrease rapidly. A locking point was defined as the first three consecutive measurements at which there was no change in height followed by 3 more consecutive height measurements at the next lowest height. Typical values were between 40 and 75 gyrations for the materials studied. High values represent mixes which will require more compactive effort in the field.

The AASHTO R 35 (2009) specification has five 20 year design traffic levels with four gyratory design levels such as for traffic level of (i) < 0.3 millions ESALs, (ii) 0.3 to < 3 millions ESALs, (iii) 3 to < 10 millions ESALs, (iv) 10 to < 30 millions ESALs and (v) > 30 millions ESALs the number of design gyrations (Ndesign) are (i) 50, (ii) 75, (iii) 100, (iv) 100 and (v) 125 respectively.

2.5 Use of Additives in Cold Mix

The research works to improve the cold mix by mixing with additives is mainly done in two ways. First one is adding the additives to aggregate (dry method) during the production of cold mix and the second one is adding the additives to bitumen emulsion (wet method) prior to production of cold mix. Some major additives used in the present research field are discussed below.

- **Cement**

Schmidt et al. (1973) studied the effect of adding cement in an attempt to improve the slow development of strength of emulsion-treated mixes. The cement was added to the aggregate at the time the asphalt emulsion was incorporated. Their study showed that mixes treated in this way cured faster, developed a high resilient modulus (M_r) more rapidly, and were more resistant to water damage. Terrel and Wang (1971) previously showed that the rate of development of M_r in emulsion-treated mixes was greatly accelerated by the addition of cement. Head (1974) reported the results of research on cement modified asphalt cold mixes. He indicated that addition of cement had a very significant effect on mix stability; addition of 1% cement produced an increase in stability of 250-300% over that of untreated samples. Specimens without cement immersed in water after stability tests disintegrated after 24 h, whereas cement-treated specimens indicated no deterioration. Uemura and Nakamori (1993) reported the use of normal Portland cement in emulsion mixtures for years in Japan. Li et al. (1998) conducted experiments to evaluate the mechanical properties of a three-phase cement-asphalt emulsion composite (CAEC). Through experimental investigation, they reported that CAEC possessed most of the characteristics of both cement and asphalt, namely the longer fatigue life and lower temperature susceptibility of cement concrete, and higher toughness and flexibility of asphalt concrete. Brown and Needham (2000) indicated that cement caused emulsion charges to become more positive (or less negative). Pouliot et al. (2003) aimed at understanding the hydration process, the microstructure, and the mechanical properties of mortars prepared with a new mixed binder made of a cement slurry and a small quantity of asphalt emulsion (SS-1 and CSS-1). They indicated that the cement hydration process was nominally influenced by the presence of a small quantity of emulsion. Song et al. (2006) purposed to evaluate the feasibility on the use of an asphalt emulsion as a polymeric admixture. They showed that waterproofness, carbonation resistance and chloride- ion penetration resistance of the asphalt-modified mortars were markedly improved with the increase in the polymercement ratio, while their compressive strength and adhesion to mortar substrates were reduced with the increase in polymer-cement ratio. Oruc et al. (2007) conducted experiments to evaluate the mechanical properties of emulsified asphalt mixtures having Portland Cement substituted for mineral filler in an increased percentage from 0 to 6%. The test results illustrated significant improvement with a high portland cement percentage and showed cement was an effective adhesion agent for emulsion mixtures Moreover they also suggested that the cement modified asphalt emulsion mixes might be used as a structural pavement layer. Thanaya et al. (2009) reported that the addition of 1 to 2 % of rapid-setting cement accelerated the early strength obtained as well as enhanced the mechanical performance of the modified cold mixes.

- **Fly ash**

Fly ash is used as a filler material. Traditionally, fly ashes have been used in a range of applications, namely as fill materials, for grouting, and soil stabilisation. Fly ash has also been used in road pavements as road bases, sub-bases and for sub-grade formation. Thanaya et al.

(2009) described the experimental tests and results obtained from incorporating coal combustion products (ashes) into cold bituminous emulsion mixtures (CBEMs). The coal ash used was fly ash which was used as filler in the CBEMs. The mixture properties evaluated were: volumetric properties, stiffness modulus (ITSM), and repeated load axial creep. These properties were compared with conventional cold asphalt mixtures not containing any waste/recycled materials. Fly ash was found to be very suitable for use as filler in cold bituminous mixtures. At full curing conditions, the stiffness of CBEMs were found to be very comparable to those of hot mixtures. Al-Busaltan et al. (2012) used LJMU-FA1 which was a waste domestic fly ash, within the CBEM's to improve the mechanical properties, namely Indirect Tensile Stiffness Modulus and Creep Stiffness. Five percentages of the specific waste materials from 0.5 to 5.5% of aggregate mass in the mixture was incorporated in the CBEM's. The results illustrated a comparative enhancement in the mechanical properties of the new cold mixtures. Asi and Assaad (2005) studied the effect of Jordanian oil shale fly ash on asphalt mixes. It indicated that oil shale fly ash modification improved the resilient modulus and the dynamic creep test of the modified mixes as compared to the control mix.

- **Lime**

Wang and Sha (2010) in a study indicated that the limestone and limestone filler impact upon hardness was significant when compared with granite and granite fillers.

- **Fiber**

Benedito et al. (2003) studied the effect of the addition of polypropylene fiber on the mechanical properties of dense graded cold mix asphalt mixture. The results showed that the addition of fiber was responsible for a small variation in mixture strength parameters, as well as for substantial drops in mixture resilient moduli when compared to plain mixtures.

- **Chemical products**

Suliman and Awwad (2000) used the oil shale as an extender to the asphalt cement. The shale oil binders displayed inconsistent physical properties, which could be attributed to the incompatibility of the oil shale with the asphalt cement or due to improper blending of the oil shale with the asphalt cement. Edwards et al. (2006) studied the effects of commercial waxes on asphalt concrete mixtures. The results (dynamic creep test) showed that the smallest strain was recorded for the asphalt mixture with bitumen containing commercial waxes, indicating better resistance to rutting. Chavez-Valencia, Alonso, Manzano, Perez, Contreras, and Signoret (2007) indicated that when bitumen emulsion was modified with the solution of polyvinyl acetate emulsion (PVAC-E), it resulted in the increment of the compressive strength of the cold mix, hence a pavement made by this modified cold mix could show improved resistance to the rutting and fatigue caused by the heavy traffic loads. Borhan et al. (2009) conducted to evaluate the application of used cylinder oil (UCO) in the preparation of asphalt concrete. The mechanical properties of the modified asphalt mixtures were examined and compared with a conventional mixture. The physical properties of UCO were first analyzed. Different percentages of UCO (0%, 5%, 10%, 15%, and 20%) were used as solvent material for the preparation of asphalt concrete mixes. All samples were tested for Marshall stability, indirect tensile strength, indirect tension, and static and dynamic creep. The addition of UCO was observed to soften the asphalt-UCO binders. The results indicated that the effects of UCO in asphalt concrete mixes depended on the percentage of

UCO used in the mixtures and also on the chemical interaction between the UCO and the asphalt.

2.6 Effect of Aggregate Gradation

Some aggregate gradation design formulas by Fuller and Thompson (1907), Roberts et al. (1996) and Cooper et al. (1985) provided the maximum dense gradations. But in the first two cases only one gradation curve and in the last case some more gradation curves could be designed which may not fall within a specified gradation limit. Only Bailey method is available which not only designs the aggregate gradation by considering both blend by weight and blend by volume but also provides numbers of aggregate gradation within the gradation limit.

Vavrik, Pine, Bailey (2002) thoroughly elaborated the concept behind the Bailey method. It uses two principles that are the basis of the relationship between aggregate gradation and mixture volumetrics:

- Aggregate packing
- Definition of coarse and fine aggregate.

With these principles, the primary steps in the Bailey Method are:

• Combine aggregates by volume, and

• Analyze the combined blend.

Traditionally coarse aggregate is defined as any aggregate that is retained by the 4.75 mm sieve. Fine aggregate is defined as any aggregate that passes the 4.75 mm sieve. In the

Bailey method, the sieve which defines coarse and fine aggregate is known as the primary control sieve (PCS), and the PCS depends on the nominal maximum particle size (NMPS) of the aggregate blend. The PCS is defined as the closest sized sieve to the result of the PCS formula given as:

$$PCS = NMAS \times 0.22 \qquad 2(iii)$$

Where, PCS = primary control sieve for the overall blend

NMAS = NMAS for the overall blend, which is one sieve larger than the first sieve that retains more than 10% (as defined by Superpave terminology)

The following three important ratios considered in the Bailey method are described below. In case of fine graded mix the original PCS is treated as NMAS and all other parameters must be found out as per this new NMAS.

- CA ratio: This ratio describes how the coarse aggregate particles pack together and, consequently, how these particles compact the fine aggregate portion of the aggregate blend that fills the voids created by the coarse aggregate. As it increases, VMA increases.

CA ratio = (% Passing Half Sieve - % Passing PCS) / (100% - % Passing Half Sieve) 2(iv)

Understanding the packing of coarse aggregate requires the introduction of the half sieve. The half sieve is defined as one half the NMAS. Particles smaller than the half sieve are called “interceptors.” Interceptors are too large to fit in the voids created by the larger coarse aggregate particles and hence spread them apart.

- FA_c ratio: This ratio describes how the coarse portion of the fine aggregate packs together and, consequently, how these particles compact the material that fills the voids it creates. As it increases, VMA decreases.

  $$FA_c = (\% \text{ Passing SCS}) / (\% \text{ Passing PCS}) \qquad 2(v)$$

  In this case, SCS (Secondary Control Sieve) = 0.22 x PCS

- FA_f ratio: This ratio describes how the fine portion of the fine aggregate packs together. It also influences the voids that will remain in the overall fine aggregate portion of the blend because it represents the particles that fill the smallest voids created. As it increases, VMA decreases.

  $$FA_f = (\% \text{ Passing TCS}) / (\% \text{ Passing SCS}) \qquad 2(vi)$$

  In this case, TCS (Tertiary Control Sieve) = 0.22 x SCS

In the Bailey method, coarse-graded mix is defined as mixtures which have a coarse aggregate skeleton. Fine-graded mixtures do not have enough coarse aggregate particles (i.e., larger than the PCS) to form a skeleton, and therefore the load is carried predominantly by the fine aggregate. To select a chosen unit weight the designer needs to decide if the mixture is to be coarse-graded or fine-graded. The loose unit weight is the lower limit of coarse aggregate interlock. The rodded unit weight is generally considered to be the upper limit of coarse aggregate interlock for dense-graded mixtures. This value is typically near 110% of the loose unit weight. For dense-graded mixtures, the chosen unit weight is selected as a percentage of the loose unit weight of coarse aggregate. If the aim is to obtain some degree of coarse aggregate interlock (as with coarse-graded mixtures), the percentage used should range from 95% to 105% of the loose unit weight. With fine-graded mixtures, the chosen unit weight should be less than

90% of the loose unit weight. For all dense-graded mixtures, it is recommended not to use a chosen unit weight in the range of 90% to 95% of the loose unit weight. Dense graded mixtures designed in this range have a high probability of varying in and out of coarse aggregate interlock in the field with the tolerances generally allowed on the PCS. For SMA mixes, the chosen unit weight for the coarse aggregates should be 110% to 125% of their corresponding rodded unit weight.

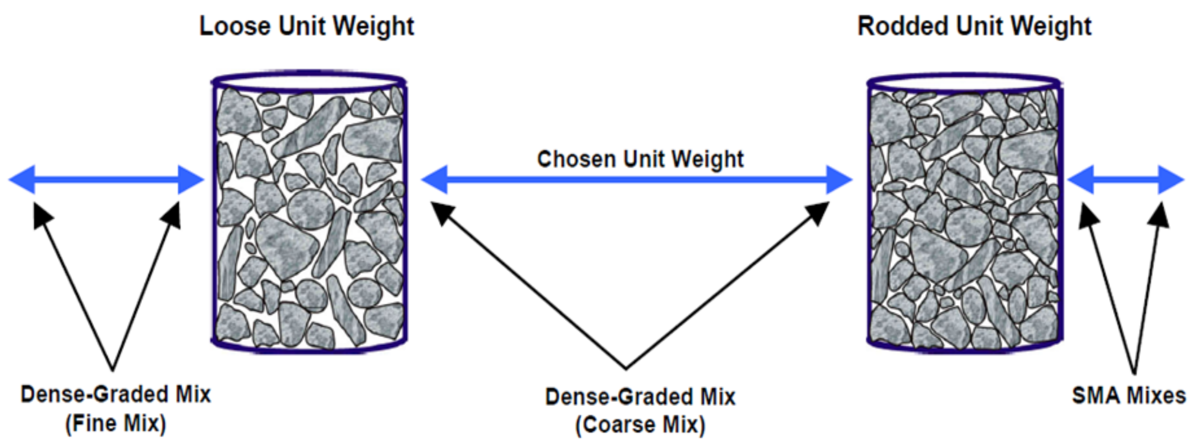

Figure 2.1 Selection of chosen unit weight of coarse aggregate (Vavrik, Pine, Bailey; 2002)

The calculations to evaluate a blend can be done manually using a calculator, but it was recommended to construct a spreadsheet to do the calculations. To evaluate an existing design, some of the input variables must be estimated and the calculated gradation should be compared with the actual gradation. Adjustments should be made to the input variables until the calculated and actual gradations became as close as possible. This process would be time consuming without a spreadsheet.

The three input variables to be estimated are:

- Chosen unit weight of coarse aggregate
- Volume of coarse aggregate
- Volume of fine aggregate
- After adjusting the input variables to obtain a calculated gradation that matches the design gradation, the three Bailey ratios (CA, FA_c, and FA_f) for the mix would be available.

The Bailey method does not directly account for the shape and texture of the aggregate source, but does approximate the shape of aggregate from the loose and rodded unit weights. The predicted change in VMA according to Bailey could be significantly changed due to the change in aggregate characteristics. The Bailey method indicates potential construction problems when the aggregate ratios are considered out of range according to the Bailey criteria. The magnitude of these problems could be evaluated as the aggregate ratios change from mixture to mixture.

2.7 Summary

From the review of literature, it has been found that the mechanical properties of the cold mix are affected by a number of parameters including aggregate gradation, type of emulsion, level of compaction, void content, curing time, and additives such as cement. Though mechanical properties of cold mix asphalt mixtures can be improved by incorporating cementitious materials such as ordinary portland cement and rapid setting cement, but unfortunately, these materials are charged at additional cost and have a considerable CO_2 impact. Therefore, attempts should be made to address some cost effective and more environmental friendly materials utilising the waste or by product. The cold mix design recommendations provided by Thanaya was found to be accepted by many researchers. It has been also found that Bailey method for gradation selection is the only method available which analyses the aggregate gradations considering both blend by volume as well as blend by weight.

In next chapter the detailed experimental methodology of the present study is provided.

Chapter 3

Experimental Investigations

3.1 Introduction

This chapter highlights the experimental works conducted throughout the project. It presents the methodology of experimental program to accomplish the overall framework of the present study stated in section 1.3 and also deals with experiments carried out on the materials and detailed test procedures for cold mixes.

3.2 Methodology of Experimental Program

In the study, both dense (BC) and gap (SMA) graded cold mixes were prepared. Selection of materials and aggregate gradations was as per specifications specified later. For compaction of cold mixes, both Marshall compaction and gyratory compaction were followed. MORTH (2001) specification, Asphalt Institute Manual Series 14 (1997) and the recommendations provided by Thanaya (2007) were taken in to consideration for the selection of cold mix design procedure. Effects of compaction level in both methods of compaction as well as the effects of additives such as cement, lime and fly ash on properties of cold mixes were observed. For both types of cold mixes (BC, SMA) six numbers of modified aggregate gradations were designed within the initially adopted gradation limits. These six gradations were produced by combining two values (maximum, minimum) of CA ratio and three values (maximum, minimum, middle) of filler quantities. The overall methodology of experimental program is described through the block diagram in figure 3.1.

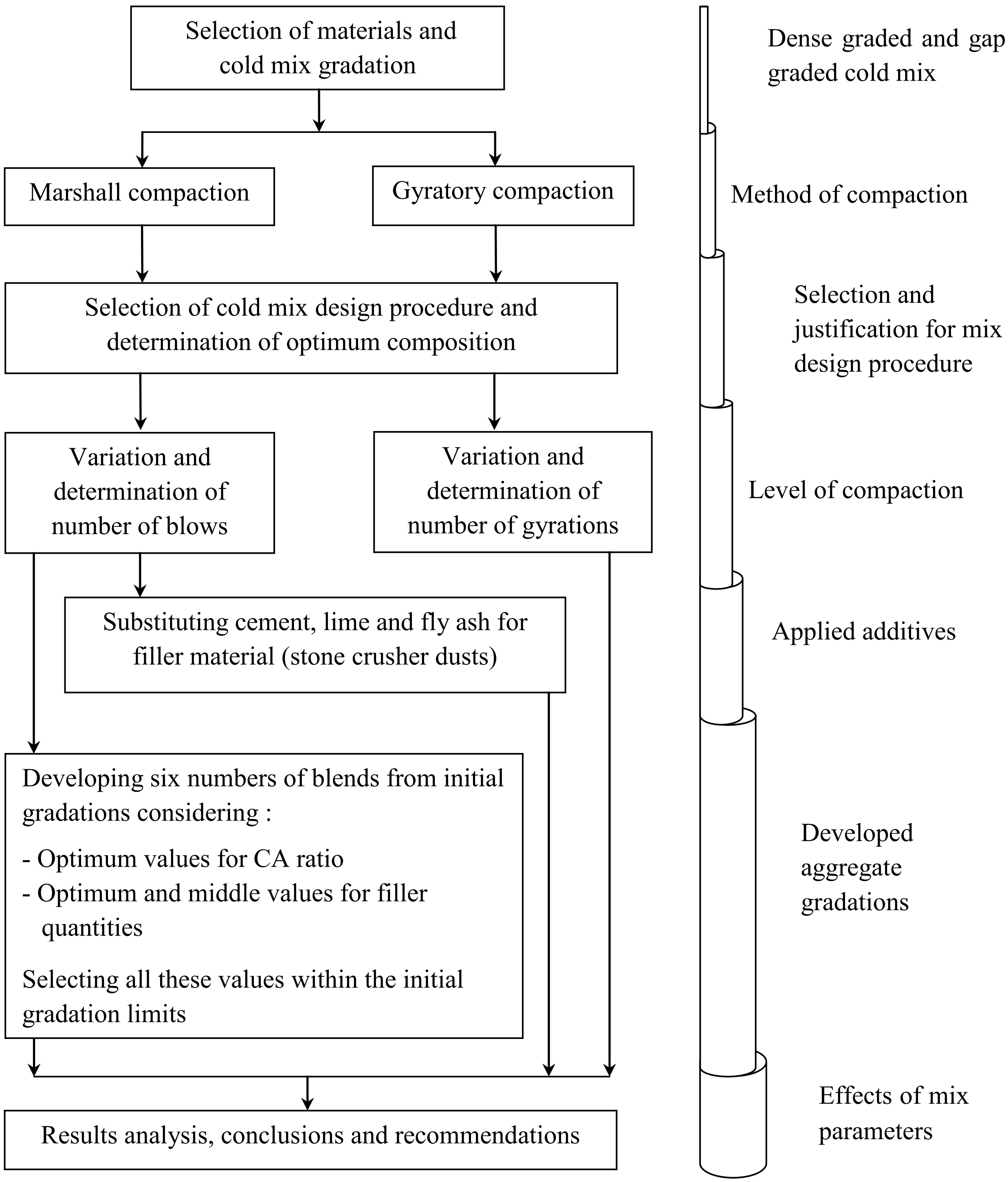

Figure 3.1 Methodology of experimental program

3.3 Selection of Cold Mix Design Procedure

After the comparative study on the design procedures summarised in table 2.1 and considering the design requirements as per MORTH provided in table 2.2., the suitable cold mix design procedures followed in the present study for both method of compaction are briefly illustrated in table 3.1. There are few differences between the adopted design procedures for both method of compaction (Marshall, gyratory) and the concept behind this is explained later in result and discussion sighted in chapter four.

Table 3.1 CMA design procedure for present study

Marshall compaction	Gyratory compaction
Determination of ➢ Aggregate gradation (As per specifications) ➢ IRAC and IEC (As per MS 14 formula) ➢ OPWC (Coating Test) ➢ 50 blows of compaction level (as per MORTH) ➢ OTLC (Dry Stability Test) ➢ ORAC (Soaked Stability Test) ➢ Retained Stability (Dry Stability Test at ORAC)	Determination of ➢ Aggregate gradation (As per specifications) ➢ IRAC and IEC (As per MS 14 formula) ➢ OPWC (Coating Test) ➢ Compaction Level i.e. number of gyrations to achieve air void target (Dry Stability Test) ➢ OTLC (Dry Stability Test) ➢ ORAC (Soaked Stability Test) ➢ Retained Stability (Dry Stability Test at ORAC) ➢ Increase in compaction Level to achieve air void target if required (Dry Stability Test at ORAC)

3.4 Materials Used

3.4.1 Aggregates

For preparation of cold mixes, two types of aggregate gradations such as dense gradation (BC) and gap gradation (SMA) were taken as per MORTH (2001) and IRC:SP:79 (2008) specifications and was given in table 3.2 and table 3.3 respectively.

3.4.1.1 Coarse Aggregates: Raw materials consisted of stone chips were collected from a local source. Aggregates up to 4.75 mm IS sieve size were used as coarse aggregate. Its specific gravity was found to be 2.75 as per IS: 2386 (Part-III) procedures. Standard test was conducted to determine some other physical properties and is summarized in table 3.4.

3.4.1.2 Fine Aggregates: Raw materials consisted of stone crusher dusts were collected from a local crusher. Aggregates with fractions passing 4.75 mm and retained on 0.075 mm IS sieve were used as fine aggregates. Its specific gravity was found to be 2.62 as per IS: 2386 (Part-III) procedures.

3.4.2 Filler

Raw materials for stone crusher dusts were collected from a local crusher while fly ash, lime and portland slag cement (Grade 43) were collected from local market. Materials passing 0.075 mm IS sieve was used as filler material. Specific gravity for stone crusher dusts, fly ash, lime and cement were found to be 2.7, 2.2, 2.3 and 3.07 respectively.

3.4.3 Binder

Cationic medium setting (CMS) Bitumen emulsion collected from the reliable source was used in this investigation to prepare the samples. Its residual asphalt content was found to be 65.4%. Some of its important physical properties are given in table 3.5.

Table 3.2 Adopted dense gradation (BC) for aggregate

Nominal maximum aggregate size 19 mm		
Sieve size (mm)	Specified limit (%)	Percentage passing
26.5	100	100
19	90-100	95
9.5	60-80	70
4.75	35-65	50
2.36	20-50	35
0.30	3-20	12
0.075	2-8	5

Table 3.3 Adopted gap gradation (SMA) for aggregate

Nominal maximum aggregate size: 13.2 mm		
Sieve size (mm)	Specified limit (%)	Percentage passing
19	100	100
13.2	90-100	94
9.5	50-75	62
4.75	20-28	28
2.36	16-24	24
1.18	13-21	21
0.600	12-18	18
0.300	10-20	16
0.075	8-12	10

Table 3.4 Physical Properties of coarse aggregate

Property	Test Method	Test Result
Aggregate Impact Value (%)	IS: 2386 (Part-IV)	14.4
Aggregate Crushing Value (%)	IS: 2386 (Part-IV)	13.01
Los Angels Abrasion Value (%)	IS: 2386 (Part-IV)	18
Flakiness Index (%)	IS: 2386 (Part-I)	18.84
Elongation Index (%)	IS: 2386 (Part-I)	21.4
Water Absorption (%)	IS: 2386 (Part-III)	0.14

Table 3.5 Physical properties of bitumen emulsion (CMS)

Property	Test Method	Test Result
Viscosity by Say bolt Furol Viscometer at 50° C in seconds	IS : 8887-2004	120
Residue by evaporation in %	IS : 8887-2004	65.4
Residue Penetration at 25° C, 100g, 5 Sec in 0.1 mm	IS : 8887-2004	84
Residue Ductility at 27° C in cm	IS : 8887-2004	95
Residue specific gravity	IS : 1202-1978	1.01

3.5 Preparation and Testing of samples

The mixes were prepared according to the cold mix design procedure given in table 3.1. The detailed justification behind the adopted design concept and its validation is given in chapter four. The whole process is illustrated in the next paragraphs.

1. The validation of design procedure was accomplished by taking two sets of IRAC for Marshall compaction method, one IRAC value was taken as per given formula and another one was taken arbitrarily. Once the efficiency of the empirical formula was proved, then the requirement of OTLC calculation was studied for both compaction method. Initially 40, 80, 100 and 120 numbers of gyrations were used to determine the required compaction level. These were taken from the literature review. Then the optimum residual asphalt content (ORAC) was found out for both aggregate gradations using stone crusher dusts as filler material.

2. In case of Marshall compaction, the effect of compaction level on properties of cold mixes was studied at ORAC only. The number of blows was varied from 50 to 75 blows per each face of compacted specimen. In case of gyratory compaction 40, 80, 100, 120 numbers of gyration were tried at IRAC only.

3. In next stage cement, lime and fly ash were substituted separately for stone crusher dusts in the mix composition that was found for Marshall compaction at ORAC only. In case of dense gradation (BC) the substitution was done in a range of 1 to 5 % with 1 % increment and in case of gap gradation (SMA) 2, 4, 5, 6, 8 and 10 % substitutions were done. In this study the stone crusher dust was used as the primary filler material while the secondary filler materials (cement, lime, fly ash) were used as additives. Instead of finding ORAC in case of all additives, the study aimed to observe the effect of different composition at the obtained ORAC to maintain the consistency in the study.

Up to this stage the mix properties were analysed by determining Marshall properties of the compacted mixes.

4. Finally to study the effect of aggregate gradation the Bailey concept for aggregate packing was referred. In the present study some important points taken in to consideration for the gradation design were discussed below.

    - Numbers of blends designed in each gradation (BC, SMA) were obtained by combining two optimum values (maximum, minimum) of CA ratio and three values of filler quantity (optimum and middle) taken within the initially adopted gradation limits. Hence, total six numbers of aggregate gradations were developed from the initial gradation in each type of CMA (BC, SMA) mixture.

    - During the iteration process for gradation design, percentage of passing for 4.75 mm sieve was kept constant to maintain the coarse aggregate (as per the traditional definition) fraction in all gradations. In other words the sum of percentage of fine aggregates and filler material was kept constant. Hence in the developed aggregate gradations adjustments were done within the coarse aggregate fraction itself and within the fine aggregate and filler material fractions as a whole. This was done to clearly observe the effect of aggregate packing as it provided some aggregate blends with the same fractions of coarse aggregate, fine aggregate and filler material as the initial one. Besides this it also avoided much complicacy in the study.

    - As per recommendations provided by Thompson (2006), instead of modifying the percentage of passing for SCS and TCS sieves only, other sieves below the SCS sieve should also be considered for more efficient design. During the iteration process for gradation design it was observed that by varying the filler quantity within the initial gradation limit the ratios for all sieves below the SCS sieve got modified effectively for each variation in filler quantity.

For improving the initial gradations first of all the equivalent Bailey gradation curve for the existing gradation was found out to confirm the mix type and to get the initial Bailey parameters (CA, $FA_{c,}$ FA_f ratios). This process consisting of three stages is explained in figure 3.2.

Some assumptions made in Bailey method are presented below.

- Chosen unit weight (CUW): As a starting point the loose unit weight for each coarse aggregate was selected as their chosen unit weight while that in case of fine aggregate it was taken as their respective rodded unit weight.
- Blend by volume: As a starting point, in case of coarse aggregate the blend by weight (as 100% coarse aggregate) was taken as blend by volume. Similarly, as a starting point for fine aggregate the blend by weight (as 100% fine aggregate) was taken as blend by volume.

Some formulas referred from Bailey method (2000) used in stage 1 and detailed procedures for obtaining equivalent Bailey gradation curve are given below.

- ➢ In stage 1 data regarding the existing aggregate gradation, loose unit weight, rodded unit weight and bulk specific gravity of aggregate was collected. Then the initial Bailey ratios were determined.
- As a starting point selection of the CUW and blend by volume analysis was done as per the assumptions stated earlier. Estimation of blend by volume for each individual aggregate was done considering coarse aggregate as 100 % and fine aggregate as 100 % separately.

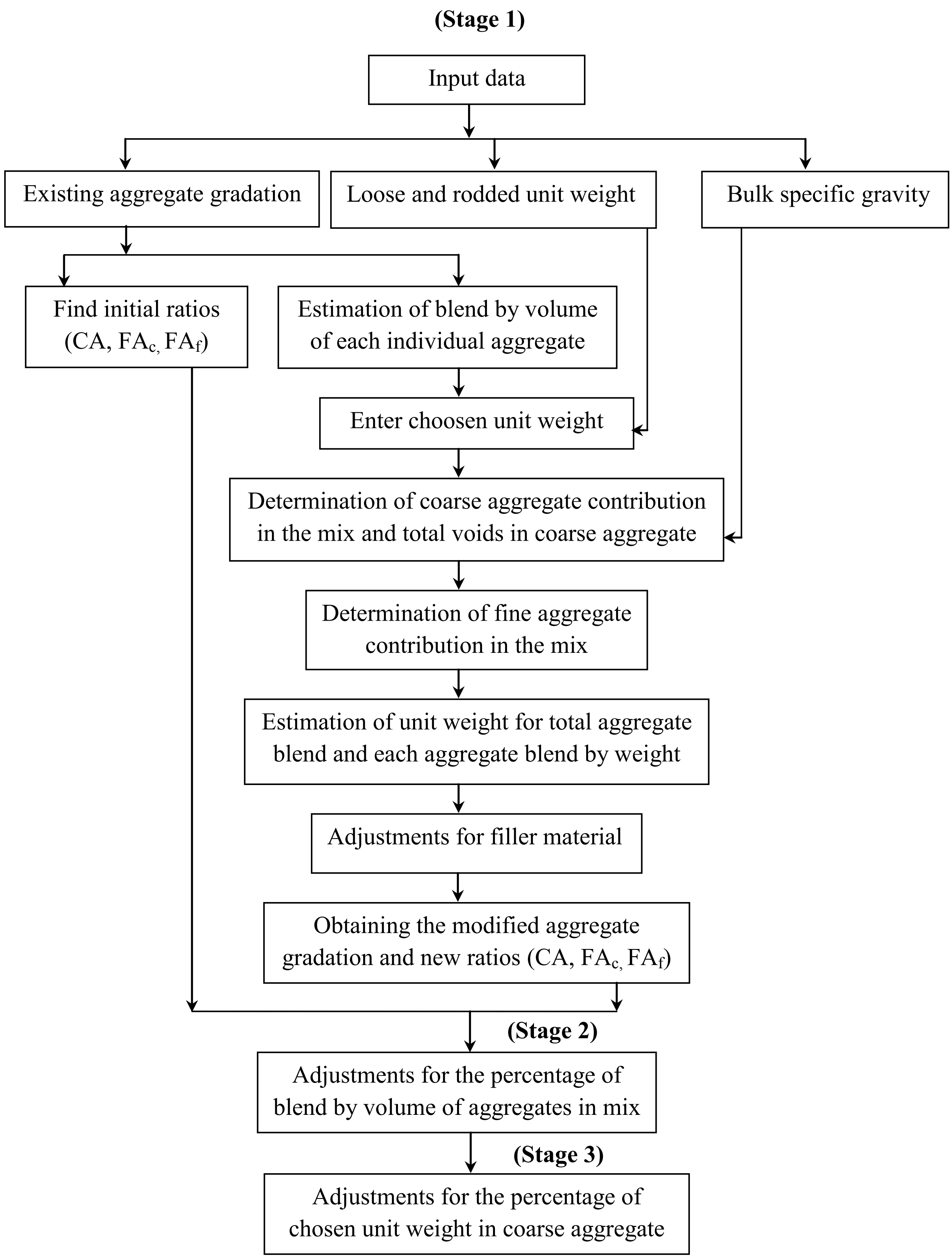

Figure 3.2 Method for obtaining equivalent Bailey gradation curve

- Contribution of coarse aggregate = (% coarse aggregate) × (chosen unit weight) 3(i)
- Voids in coarse aggregate =

  [1 – (chosen unit weight / (bulk specific gravity × 1000))] × (% Blend) 3(ii)
- Contribution of each fine aggregate = (fine aggregate chosen unit weight) × (% fine aggregate blend) × (% voids in coarse aggregate) 3(iii)
- Unit weight for the total aggregate blend = summation of the unit weight of each aggregate 3(iv)
- The initial blend percentage by weight of each aggregate = the unit weight of each aggregate / the unit weight of the total aggregate blend 3(v)
- Adjustment for filler material was done by deducting the desired filler percentage from the summation of fine aggregate percentage found in initial blend. Then from the adjusted summation the final blend percentage by weight of fine aggregate was determined by maintaining the initial blend proportions. Here the initial blend considered was found in equation 3(v) and the percentage of coarse aggregate was remained same both in initial blend and final blend.
- Finally the modified aggregate gradation in terms of percentage of passing by weight for each sieve was obtained and new ratios (CA, FA_c , FA_f) were obtained.

➢ In Stage 2 and Stage 3 adjustments were made with the blend by volume of aggregates and with the percentage of the chosen unit weight for coarse aggregate respectively. Both these stages were consisted of several iterations to get the new ratios and equivalent Bailey gradation curve as close as possible to the initial ratios and existing gradation.

After getting the equivalent Bailey gradation curve some suitable adjustments were made for the FA_c and FA_f ratios for once only by varying the blend by volume of fine aggregate. Then iteration process was conducted to get the minimum CA ratio by varying the blend by volume of coarse aggregate having initial filler quantity (middle value). It produced one of the developed aggregate gradations. Then simply by substituting the filler quantity with upper limit and lower limit two more aggregate gradations were developed. The same process was carried out for maximum CA ratio which finally produced three more numbers of developed aggregate gradations. Thus six numbers of aggregate gradations were developed from the equivalent Bailey gradation curve through iteration process by varying the CA ratio and filler quantities in case of each existing gradation (BC, SMA). It was recommended to do all these processes by constructing a spreadsheet to avoid error and delay in process. In the present study all the calculations and iterations were accomplished by constructing the spreadsheets in Microsoft excel (2007).

After the gradations were designed, the optimum composition for each gradation blend was found out by Marshall compaction as per adopted cold mix design method. The Marshall properties of the above mixes were studied. Also Static Indirect Tensile Strength Test and Static Creep Test were conducted to study other mechanical properties of the mixes compacted at ORAC only. All these mixes used stone crusher dust as filler material. Cold mixes compacted with initial gradation and six improved gradations were fully cured to perform the indirect tensile strength (ITS) test at 10°C, 20°C, 30°C, 40°C and 50°C. After the ITS test static creep test was conducted at 40°C, 50°C and 60°C for cold mixes with initial gradation and the developed gradation performed best in Marshall Stability and ITS test performance point of view. In the present study for full curing, 72 hours oven curing was done at 40°C after the samples being extruded from the mould. Also the difference between the indirect tensile strength was observed for cold mixes compacted with initial gradations and cured as per adopted curing mode and 21 days curing at room temperature.

Finally the effects of mix parameters were studied on the basis of Marshall Stability and air void content of the compacted cold mixes.

3.6 Laboratory Tests

3.6.1 Marshall Test

In this method, the resistance to plastic deformation of a compacted cylindrical specimen of bituminous mixture is measured when the specimen is loaded diametrically at a deformation rate of 50 mm per minute. There are two major features of the Marshall method of mix design. (i) density-voids analysis and (ii) stability-flow tests. The Marshall stability of the mix is defined as the maximum load carried by the specimen at the specified standard test temperature. The flow value is the deformation that the test specimen undergoes during loading up to the maximum load.

The apparatus consists of mould assembly, sample extractor, compaction pedestal and hammer, breaking head, loading machine, flow meter , water bath. In the Marshall test method of mix design three compacted samples are prepared for each binder content. At least four binder contents are to be tested to get the optimum binder content. All the compacted specimens are subject to the following tests: bulk density determination, stability and flow test and density and voids analysis. The bulk density of the sample is usually determined by weighting the sample in air and in water. It may be also calculated using the weight in saturated surface dry condition. The formulas as suggested by Thanaya (2007) have been followed in the present work.

3.6.2 Gyratory compaction

The Gyratory Compactor used in the present study was entirely developed and manufactured by Matest to simulate and reproduce the real compaction conditions under actual road paving operations, hence determining the compaction properties of the asphalt. Such compaction is achieved by combining the rotary action and the vertical resultant force applied by a mechanical head. The Compactor comprises a highly rigid steel frame ensuring excellent angle control. Load is applied by an electro-pneumatic cylinder, servo-controlled by a precision pressure regulator; the height is measured by a linear transducer. Gyratory motion is generated by an eccentric high precision system allowing an easy set up with precision and constant angle of gyration. The rotation speed is controlled by an inverter through on board computer control. Using the proper perforated mould, the Compactor is able to run tests on cold mix asphalt. The acquired results are also employed in the investigation of volumetric and mechanical characteristics of the asphalt mix.

The parameters used in the present study are the 100 mm diameter mould, 1.25° gyratory angle 30 rpm gyration rate, 4.711kN vertical load on 100mm diameter specimen. The vertical load on the specimen is automatically controlled and adjusted by the electronic system.

3.6.3 Static Indirect Tensile Strength Test

Indirect tensile test is used to determine the indirect tensile strength (ITS) of bituminous mixes. In this test, a compressive load is applied on a cylindrical specimen (Marshall Sample) along a vertical diametrical plane through two curved strips which radius of curvature is same as that of the specimen. A uniform tensile stress is developed perpendicular to the direction of applied load and along the same vertical plane causing the specimen to fail by splitting. This test is also otherwise known as splitting test. This test can be carried out both under static and dynamic (repeated) conditions. The static test provides information about the tensile strength, modulus of elasticity and Poisson's ratio of bituminous mixes. The static indirect tensile strength test has been used to evaluate the effect of moisture on bituminous mixtures.

In the present study static indirect tensile strength test was conducted using the Marshall test apparatus with a deformation rate of 50 mm per minute. A compressive load was applied along the vertical diametrical plane and a proving ring was used to measure the load. A perspex water bath (270mm × 250mm × 195mm) was prepared and used to maintain constant testing temperature. Two loading strips, (75mm × 13mm × 13mm), made up of stainless steel were used to transfer the applied load to the specimen. The inside diameter of the strip was same as that of a Marshall sample (101 mm). The sample was kept in the water bath maintained at the required temperature for minimum 30 minutes before test. The perspex water bath maintained at the same test temperature was placed on the bottom plate of the Marshall apparatus. The sample was then kept inside the perspex water bath within the two loading strips. Care was taken to place the sample centrally along its vertical diametrical plane. A loading rate of 50 mm/minute was adopted. The load was applied and the failure load was noted from the dial gauge of the proving ring. The tensile strength of the specimen was calculated by using the formula given in ASTM D 6931 (2007) and mentioned in equation 3(vi).

$$St = (2000 \times P) / (\pi \times t \times D) \qquad 3(vi)$$

where, St = Indirect Tensile Strength, kPa

P = Maximum Load, N

t = Specimen height before testing, mm
D = Specimen Diameter, mm

The test temperature was varied from 10 °C to 50 ºC at an increment of 10 °C. In this test three Marshall samples were tested at a particular temperature and the tensile strength was reported as the average of the three test results.

3.6.4 Static Creep Test

For static creep test samples were prepared at their OTLC and ORAC. As per TEX-231-F (2005) static creep test procedure the test was conducted and it consisted of two stages. In first stage a vertical load of 0.55 kN was applied for 60 minutes. The deformation was registered during 10 minutes intervals using a dial gauge graduated in units of 0.002 mm and it was able to register a maximum deflection of 5 mm. Secondly, the load was removed and its deformation was registered during next 10 minutes at 5 minutes interval of time. Test temperatures of 40℃, 50℃ and 60℃ were applied in the present study. Finally a graph between time and deformation was plotted.

3.7 Summary

In this chapter the methodology of the present work as well as the preparation and test procedures of the compacted cold mixes has been thoroughly discussed. The materials used and their physical properties are also provided. The adopted cold mix design and the detailed procedure for Bailey method to improve the present aggregate gradation has been given.

Next chapter provides the test results and their analysis part.

Chapter 4

Analysis of Results and Discussion

4.1 Introduction

The results obtained for compacted samples to analyse the effect of test parameters are discussed in this chapter. Attempt has been taken to justify the adopted design procedure and ORAC value is found out. The effects of additives, method and level of compaction on the performance of cold mixes have been studied. After constructing a spreadsheet the existing aggregate gradations are improved by using Bailey concept for aggregate packing. The performance of all the developed gradations has been observed and compared with the initial gradations.

4.2 Design Justifications and ORAC Determination

Samples were compacted by Marshall method after mixing the coarse aggregate, fine aggregate and crusher dust as filler material according to the adopted aggregate gradation given in table 3.2 and table 3.3 to produce dense graded and gap graded cold mix respectively. For both types of cold mix two IRAC values were considered. One value was chosen according to the empirical formula and another value was taken arbitrarily. By using these two IRAC values two sets of mixes were produced for each gradation.

4.2.1 Dense graded cold mixes

As per the adopted design procedure given in table 3.1, Samples were produced by Marshall compaction. The test results are summarized in table 4.1 and illustrated in figure 4.1 to figure 4.2.

Table 4.1 Optimum compositions of dense graded cold mixes

IRAC by Empirical formula	IRAC by arbitrary value
IRAC = 6 %	IRAC = 4 %
IEC = 9.17 %	IEC = 6 %
OPWC = 3 %	OPWC = 4 %
OTLC = 6.17 %	OTLC = 7.07 %
ORAC = 4.6 %	ORAC = 4.6 %
Soaked Stability = 5.88 kN	Soaked Stability = 3.19 kN
Dry Stability = 6.28 kN	Dry Stability = 3.45 kN

It should be noted that both the results of dry stability and soaked stability given were the values obtained at ORAC value.

- Determination of OTLC values:

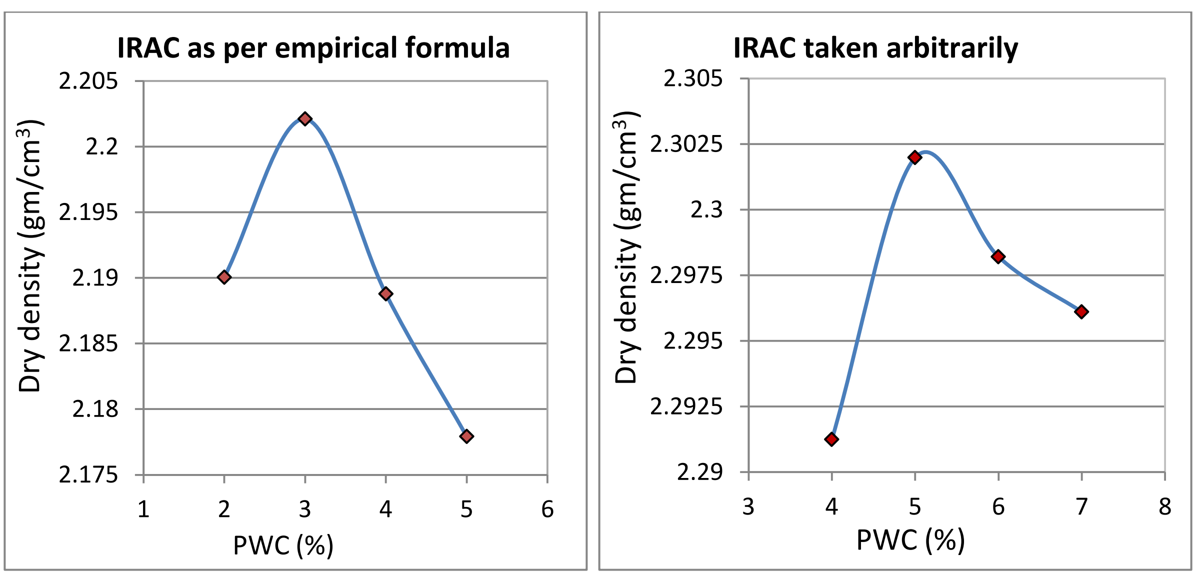

Figure 4.1 OTLC determination for dense graded cold mixes

➢ Determination of ORAC values:

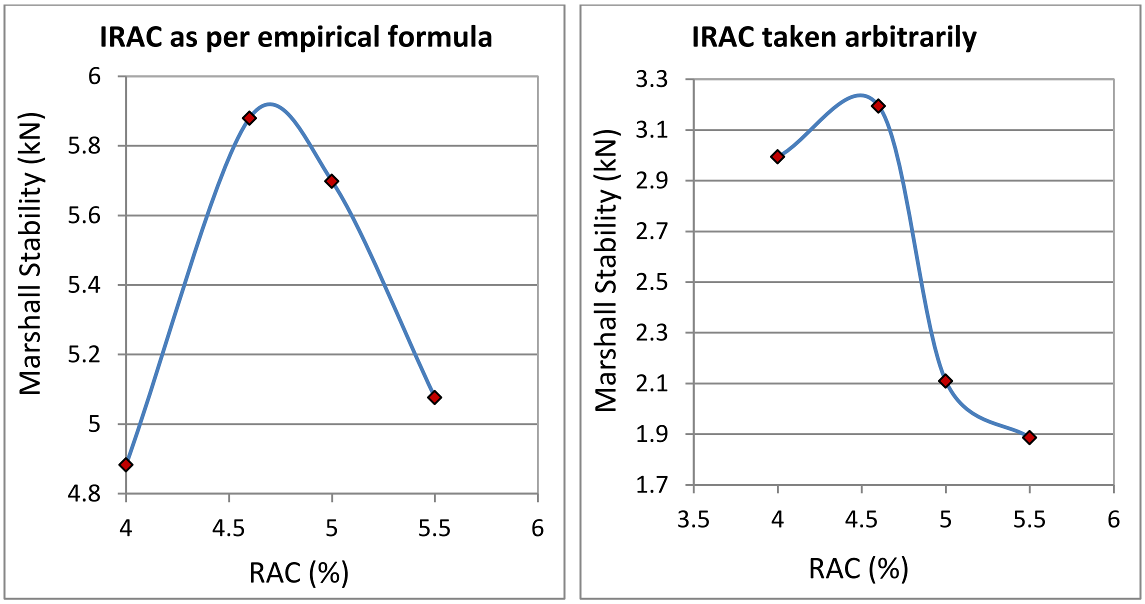

Figure 4.2 ORAC determination for dense graded cold mixes

Considering the results obtained shown in figure 4.1 to figure 4.2, it was observed that the maximum stability was achieved at RAC of 4.6 % for both types of dense graded cold mix. But the Marshall Stability was found to be greater for dense graded mix having IRAC as per empirical formula. Hence its OTLC and ORAC values were refferred for further analysis and it was presented as Cold Mix D in further study.

The other design parameters for Cold Mix D were checked at ORAC only. The flow value, air void, VMA and stability loss were found to be 3.3 mm, 8.32 %, 14.83 % and 6.35 % respectively and the test results are shown in figure 4.3.

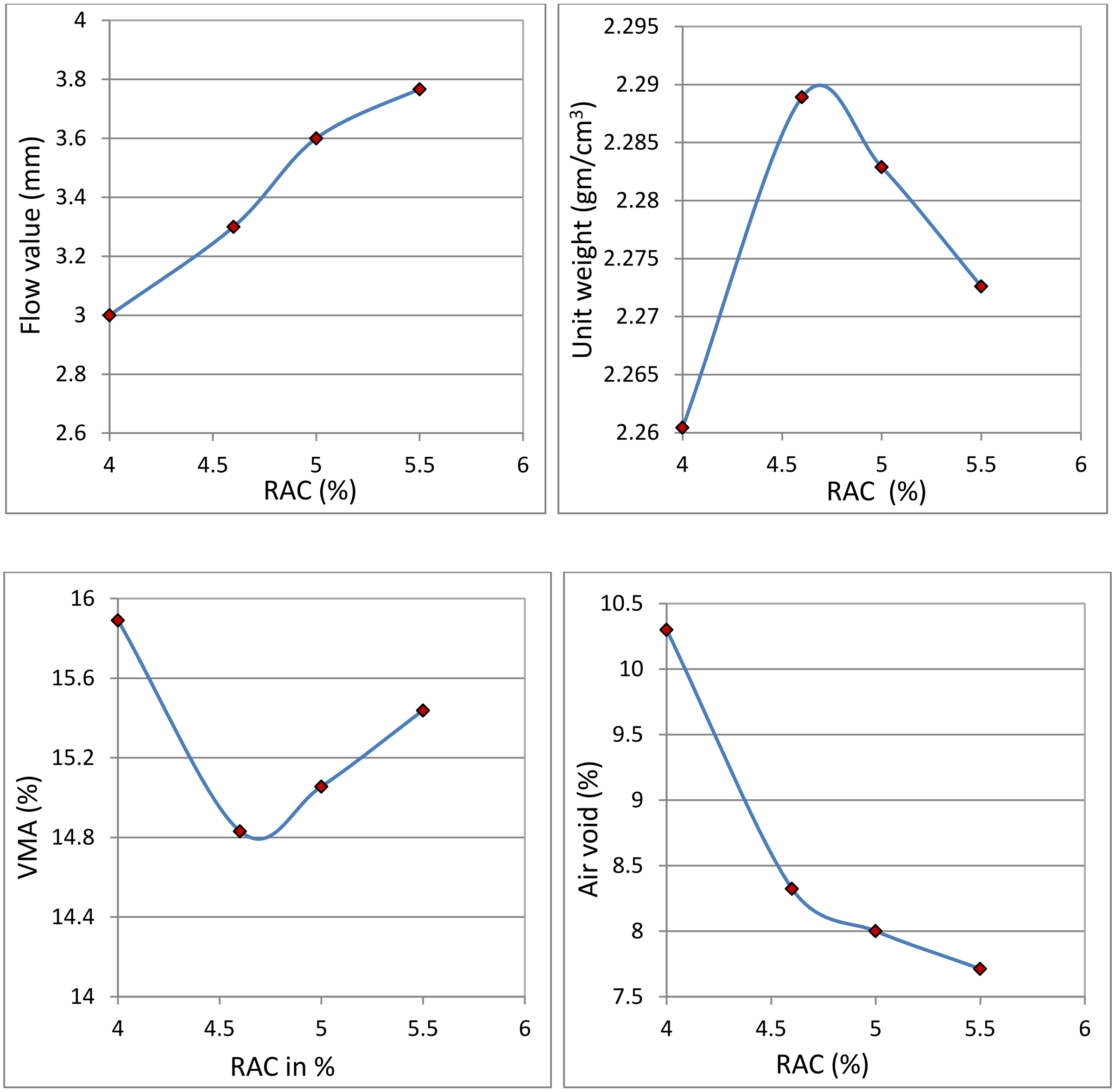

Figure 4.3 Flow value, Unit weight, VMA and Air void results of dense graded cold mix

4.2.2 Gap graded cold mixes

The test results for gap graded cold mixes are summarized in table 4.2 and illustrated in figure 4.4 to figure 4.5. It should be noted that both the results of dry stability and soaked stability given were the values obtained at ORAC value.

Table 4.2 Optimum compositions of gap graded cold mixes

IRAC by Empirical formula	IRAC by Arbitrary value
IRAC = 7 %	IRAC = 4.6 %
IEC = 10.7 %	IEC = 6.5 %
OPWC = 3 %	OPWC = 5 %
OTLC = 8.7 %	OTLC = 9.25 %
ORAC = 5.5 %	ORAC = 5.5 %
Soaked Stability = 3.46 kN	Soaked Stability = 3.1 kN
Dry Stability = 3.67 kN	Dry Stability = 3.21 kN

- Determination of OTLC values:

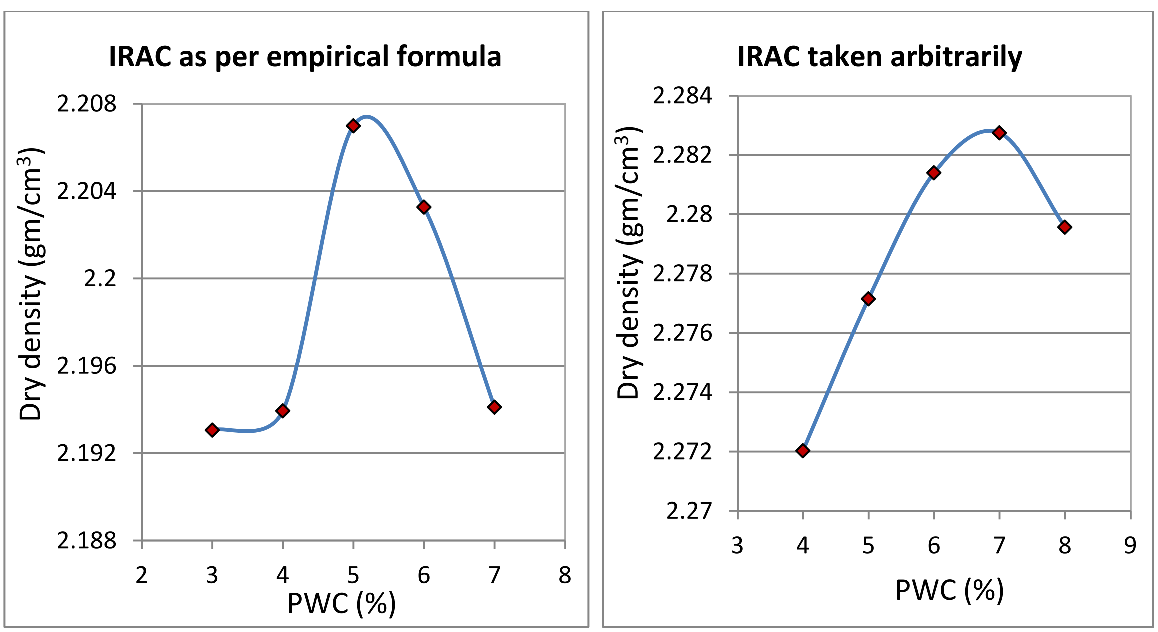

Figure 4.4 OTLC determination for gap graded cold mixes

➢ Determination of ORAC values:

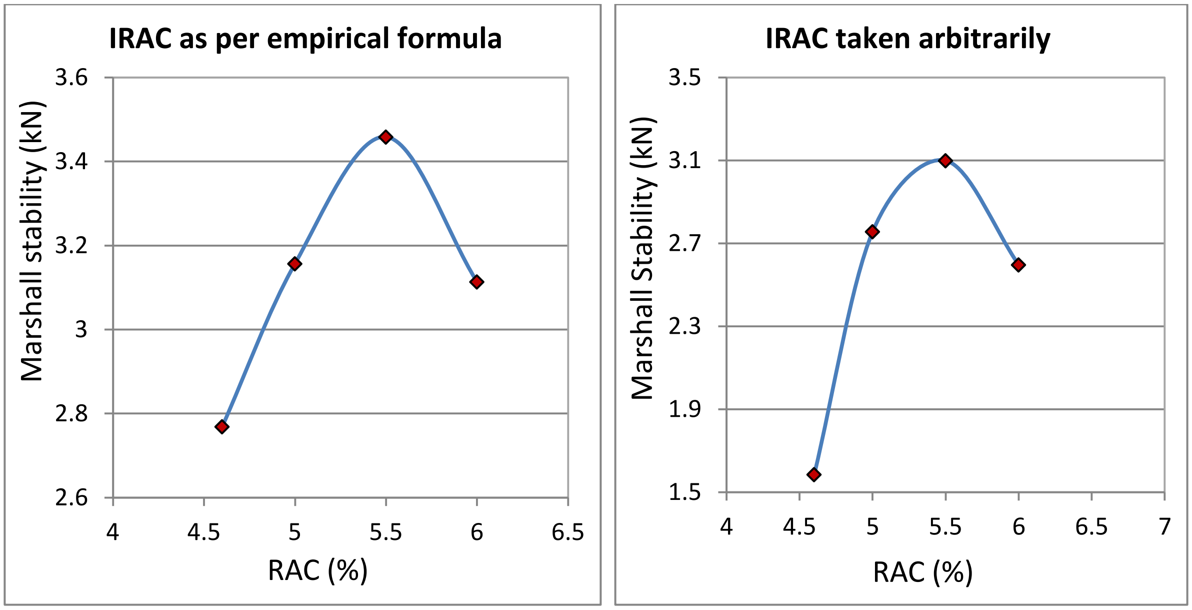

Figure 4.5 ORAC determination for gap graded cold mixes

Considering the results obtained shown in figure 4.4 to figure 4.5, it was observed that the maximum stability was achieved at RAC of 5.5 % for both types of gap graded cold mix. But the Marshall Stability was found to be greater for gap graded mix having IRAC as per empirical formula. Hence its OTLC and ORAC values were refferred for further analysis and it was presented as Cold Mix G in further study.

The other design parameters for Cold Mix G were checked at ORAC only. The flow value, air void, VMA and stability loss were found to be 3.4 mm, 9.22 %, 16.95 % and 5.87 % respectively and the test results are shown in figure 4.6.

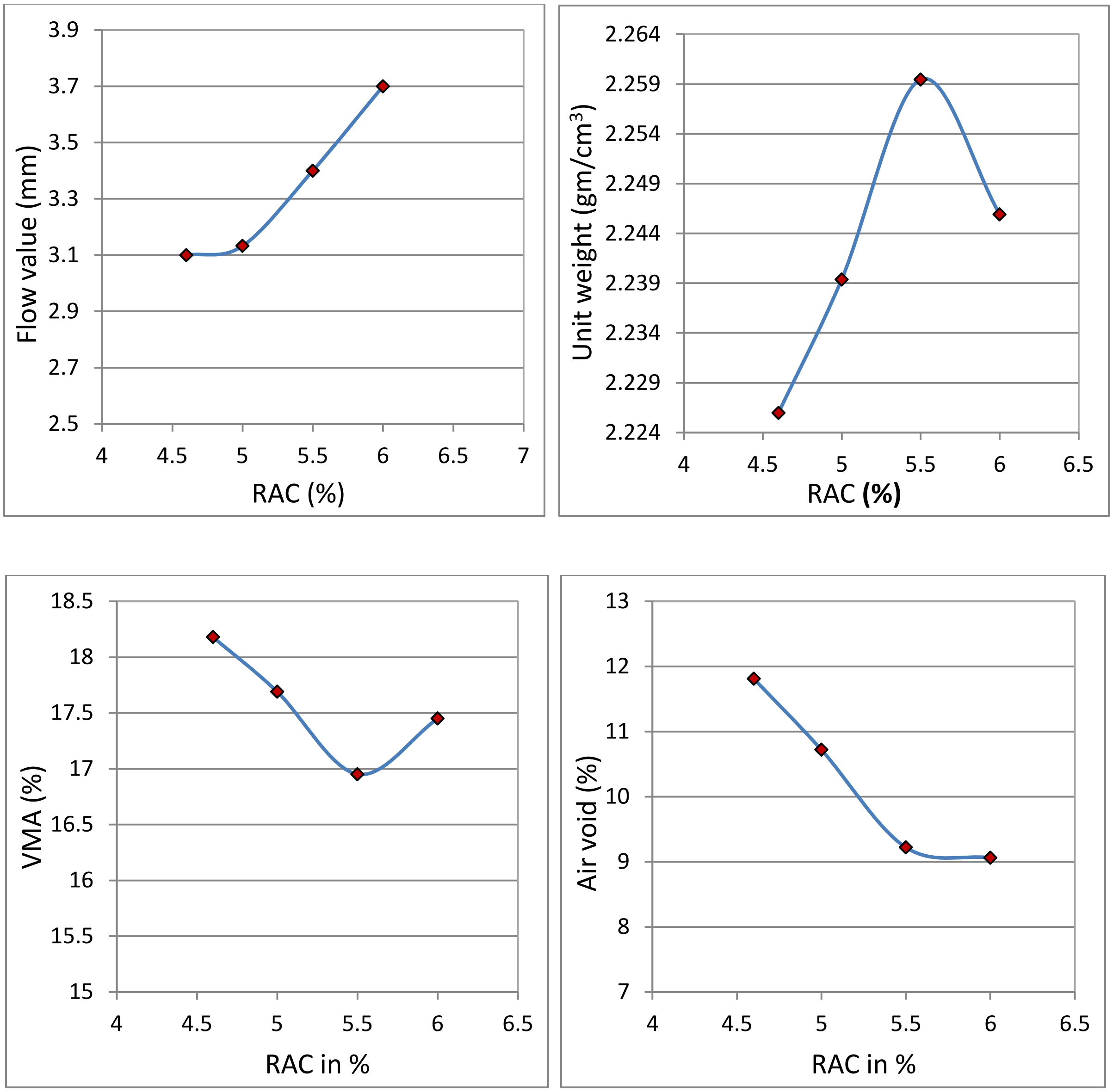

Figure 4.6 Flow value, Unit weight, VMA and Air void results of gap graded cold mix

Based on the above studies and the test results summary from table 4.1 and table 4.2 some conclusions were made which were presented below.

- ORAC values are found to be same for cold mixes having same aggregate gradation which indicates that ORAC is not affected by the IRAC and OTLC factors rather it depends on the aggregate gradation.

- Though for the same aggregate gradation ORAC is found same for both mixes produced with IRAC as per empirical formula and IRAC taken arbitrarily, it has been observed that the soaked stability of the mix having IRAC value as per empirical formula is higher. Hence it indicates that the IRAC determined by the empirical formula is more efficient in comparison to IRAC taken arbitrarily.

- It has been felt that initial stability of the mix depends on OTLC values. At same binder content higher the total liquid content, greater would be the curing time to obtain full strength of the mix. So, for laboratory procedures we should determine the OTLC value to avoid delay in work process. This concept has supported the adopted design procedure of the present study.

- While analysing the results for stability values at each ORAC, it has been observed that the dry stability value is greater than the soaked stability value for all types of cold mixes. So, in case the soaked stability has satisfied the minimum stability requirement (2.2 kN), the dry stability would also satisfy the same requirement. Hence it would be more economic to determine ORAC value on basis of soaked stability test only and the dry stability should be found out at ORAC only to check the stability loss. This supports the concept provided by Thanaya (2007).

It should be noted that all the above conclusions has been made on basis of very limited study. Hence these hypothesis need further analysis for developing more suitable design procedures.

4.2.3 Comparative study between dense and gap graded cold mix

It was observed that performance of dense graded mix (Cold Mix D) was superior than gap graded mix (Cold Mix G) in every aspect except in case of the stability loss value which was lesser for Cold Mix G.

Table 4.3 Design parameters of cold mixes at 50 blows of compaction

Design parameters	Dense graded mix (Cold Mix D)	Gap graded mix (Cold Mix G)	Design requirement
Marshall Stability	5.88 kN	3.46 kN	Min. 2.2 kN
Flow value	3.3 mm	3.4 mm	Min. 2 mm
Stability loss	6.36 %	5.87 %	Max. 50 %
Emulsion content	7% (4.6% ORAC)	8.4% (5.5% ORAC)	7 - 10 %
Air void	8.32 %	9.22 %	3 - 5 %
VMA	14.83 %	16.95 %	Cold Mix D: Min. 14 % Cold Mix G: Min. 15 %

4.3 Effect of Compaction Level

4.3.1 Dense graded cold mix

Cold Mix D (dense graded cold mix with IRAC as per empirical formula) was compacted at 75 blows of compaction with the previously found OTLC and ORAC values given in section 4.2.1. The obtained results are summarised in table 4.4.

Table 4.4 Properties of dense graded cold mix at 50 and 75 blows of compaction

Design parameters	50 blows compaction level	75 blows compaction level	Design requirement
Marshall Stability	5.88 kN	6.84 kN	Min. 2.2 kN
Flow value	3.3 mm	2.53 mm	Min. 2 mm
Stability loss	6.36 %	1.08 %	Max. 50 %
Emulsion content	7 %	7 %	7 - 10 %
Air void	8.32 %	7.44 %	3 - 5 %
VMA	14.83 %	13.47 %	Min. 14 %

It was observed that though the mix performance was improved at higher compaction level, it failed to meet the required air void target of 3 to 5 % range like the 50 blows of compaction.

4.3.2 Gap graded cold mix

Cold Mix G (gap graded cold mix with IRAC as per empirical formula) was compacted at 75 blows of compaction with the previously found OTLC and ORAC values given in section 4.2.2. The obtained results are summarised in table 4.5.

Table 4.5 Properties of gap graded cold mix at 50 and 75 blows of compaction

Design parameters	50 blows compaction level	75 blows compaction level	Design requirement
Marshall Stability	3.46 kN	3.85 kN	Min. 2.2 kN
Flow value	3.4 mm	2.57 mm	Min. 2 mm
Stability loss	5.87 %	7.56 %	Max. 50 %
Emulsion content	8.4 %	8.4 %	7 - 10 %
Air void	9.22 %	8.19 %	3 - 5 %
VMA	16.95 %	16.02 %	Min. 15 %

Like the previous case, it was observed that mix performance was improved at 75 blows of compaction. But air void range did not satisfy the required range at both 50 and 75 blows of compaction. Besides, in case of gap graded mix the stability loss was found more for 75 blows of compaction and it might be happened due to the lack of stone-to-stone contact skeleton for degradation of aggregate at higher compaction level.

Hence 50 blows of compaction was applied in further studies to produce Marshall compacted mixes.

4.4 Effect of Additives

Cement, lime and fly ash were substituted for stone crusher dust in the mix composition found for Marshall compacted dense graded and gap graded cold mix at ORAC only..

4.4.1 Dense graded cold mixes

For dense graded cold mix substitution of additives was done separately in a range of 1 to 5% with 1 % increment. The obtained test results are shown in figure 4.7.

It was observed that cold mixes with cement as an additive performed best among all mixes in every aspect. Though mixes with lime and fly ash as an additive had showed greater stability than the mixes without additive, but they resulted greater air void content with the increase in percentage of substitution. Besides, lime had improved the mix stability more efficiently than the fly ash, but it also caused higher air void content in compacted mix in comparison to fly ash.

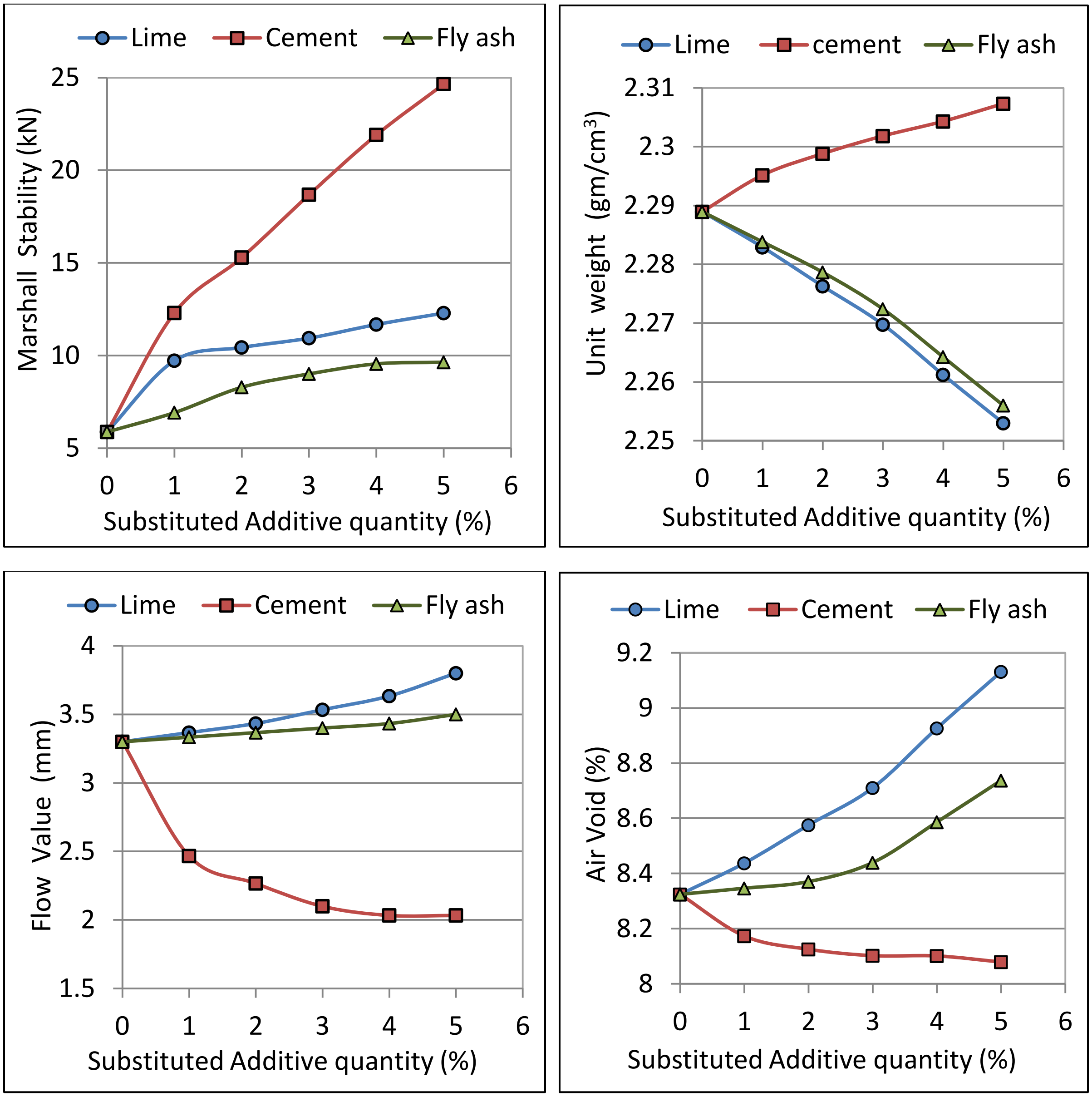

Figure 4.7 Marshall Stability, Unit weight, Flow value and Air void results of dense graded cold mix with additives

4.4.2 Gap graded cold mixes

For gap graded cold mix 2%, 4%, 5%, 6%, 8% and 10 % substitutions of additives were done separately. The obtained test results are shown in figure 4.8.

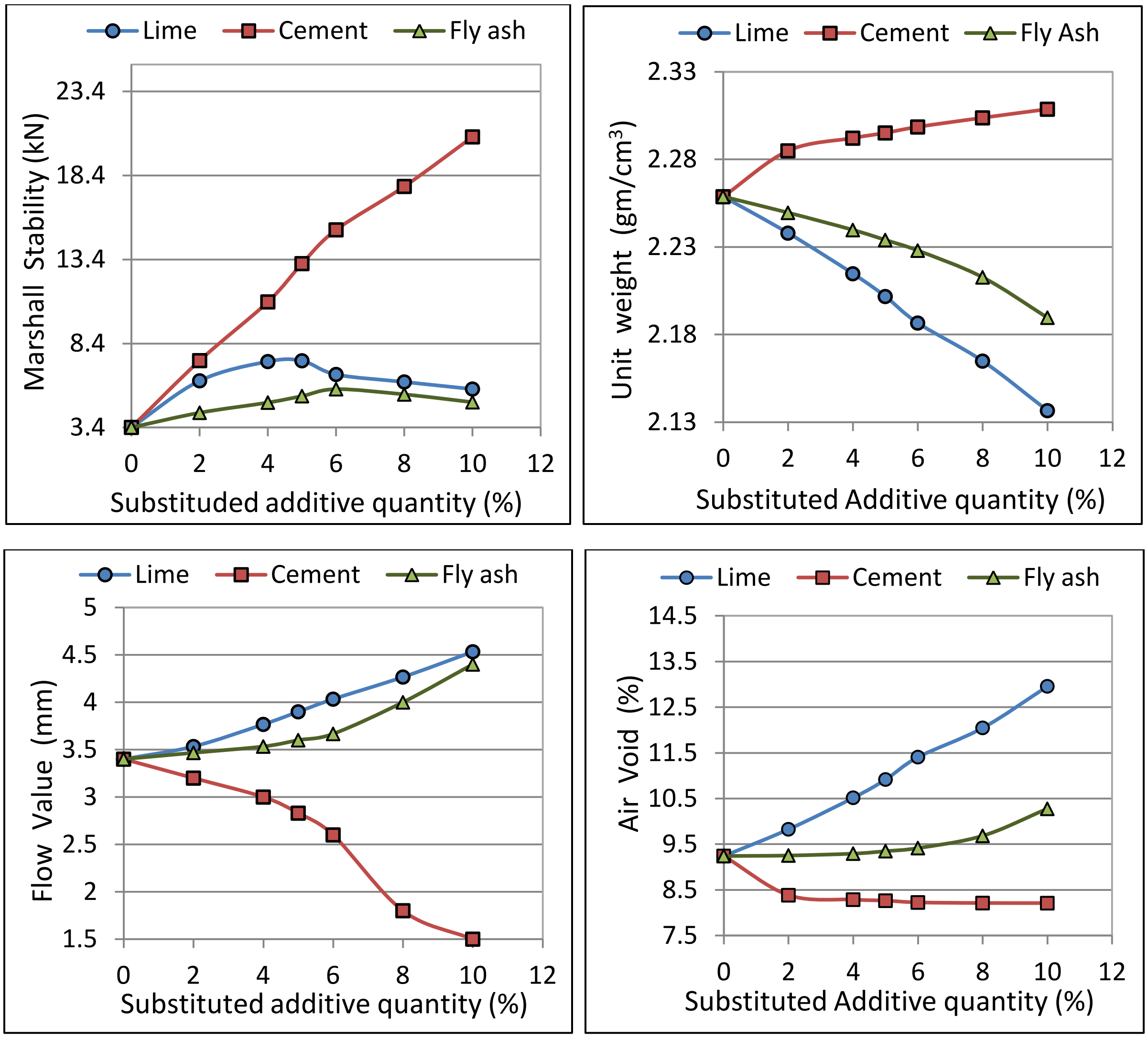

Figure 4.8 Marshall Stability, Unit weight, Flow value and Air void results of gap graded cold mix with additives

From the above Marshall test results it was observed that cold mixes with cement as an additive performed best among all mixes in every aspect as like in case of dense graded mix. Mixes with lime and fly ash as an additive had showed greater stability up to limited extent of substitution and both resulted greater air void content with the increase in percentage of substitution. In this case also mixes compacted with lime had showed greater stability but with higher air void content in comparison to mixes compacted with fly ash.

4.4.3 Comparative study between dense graded and gap graded cold mixes

➢ Results obtained by substituting cement for filler are shown in figure 4.9.

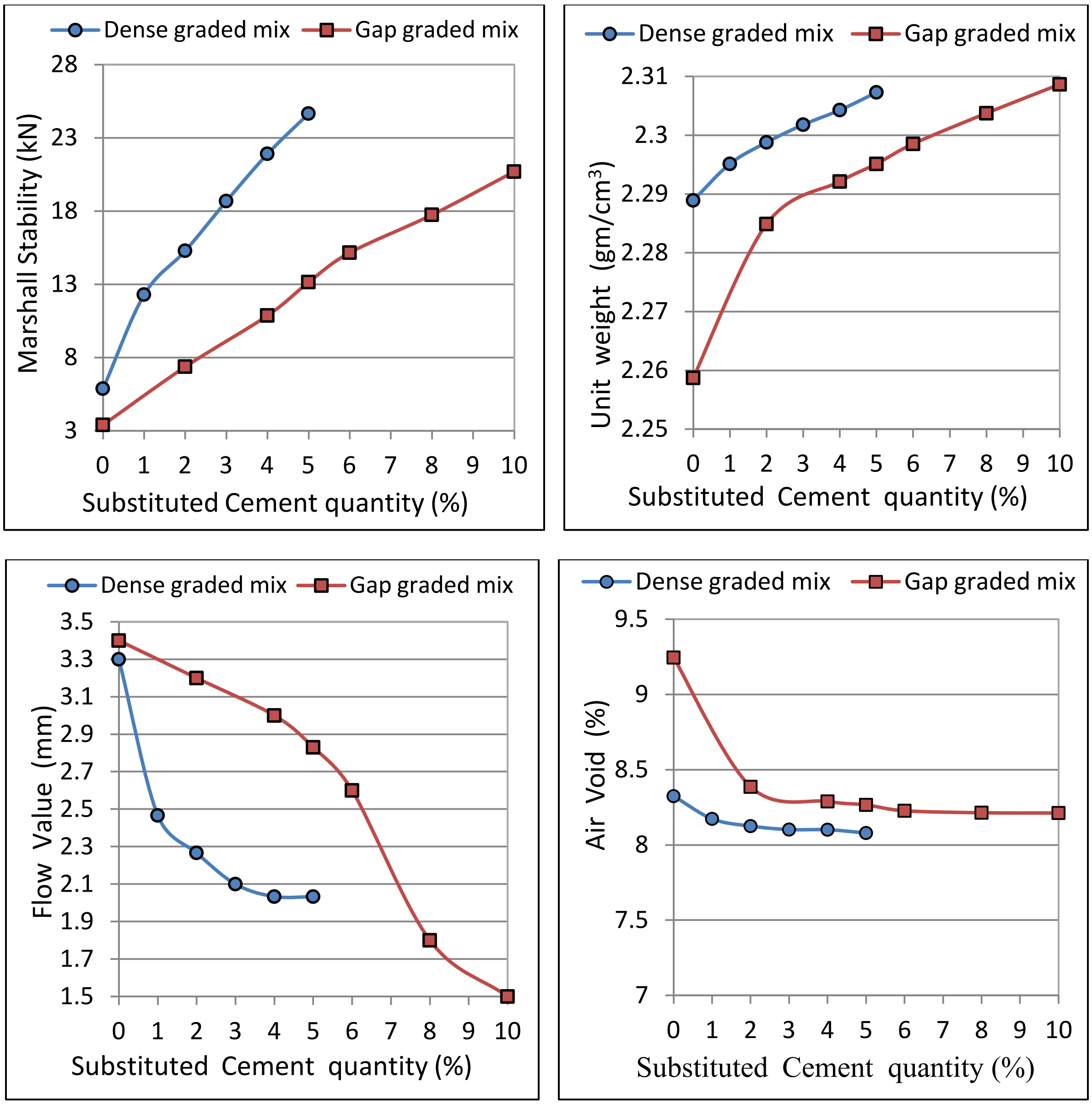

Figure 4.9 Marshall Stability, Unit weight, Flow value and Air void results of cold mixes modified with cement additive

➢ Results obtained by substituting lime for filler are shown in figure 4.10.

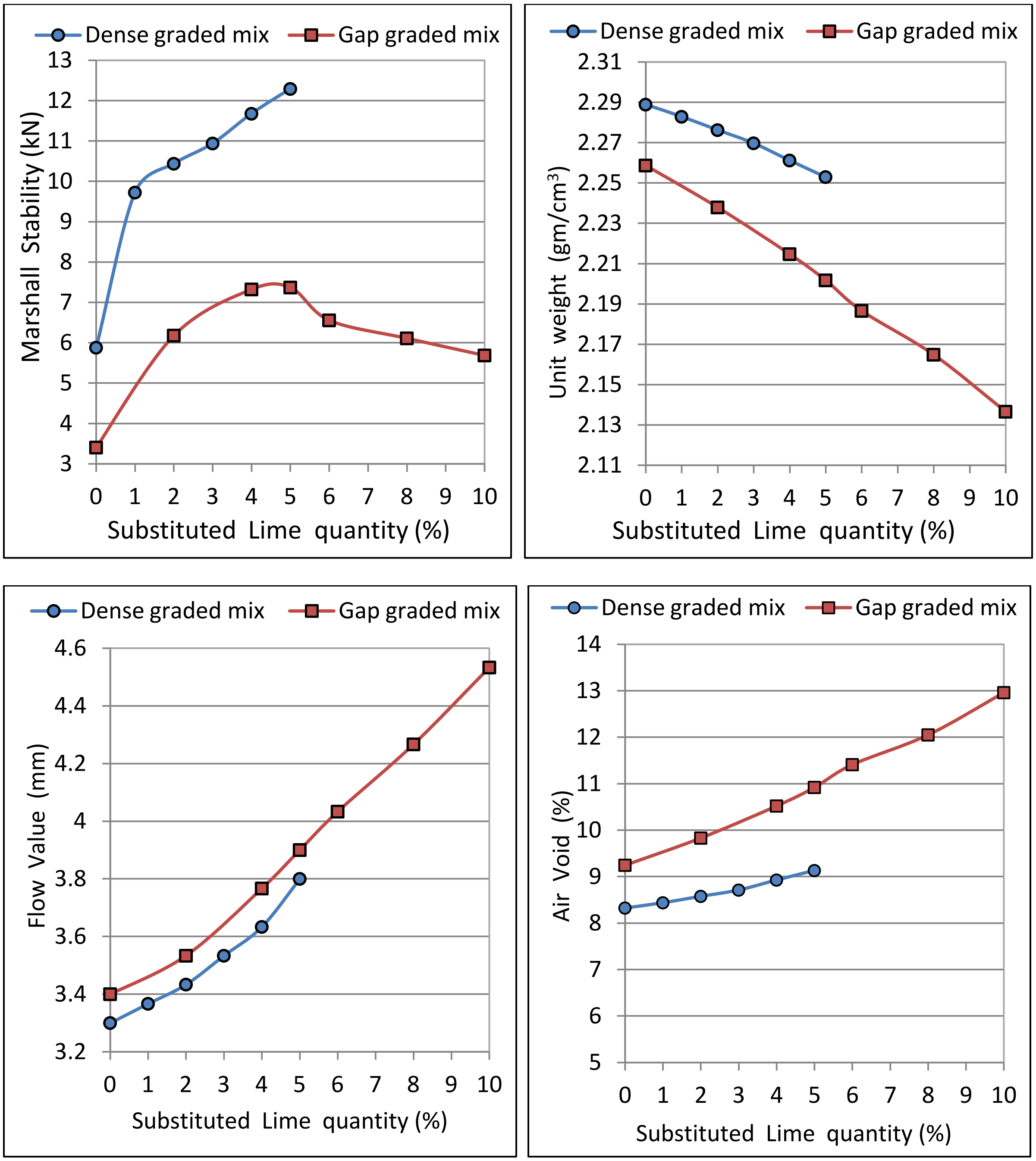

Figure 4.10 Marshall Stability, Unit weight, Flow value and Air void results of cold mixes modified with lime additive

➢ Results obtained by substituting fly ash for filler are shown in figure 4.11.

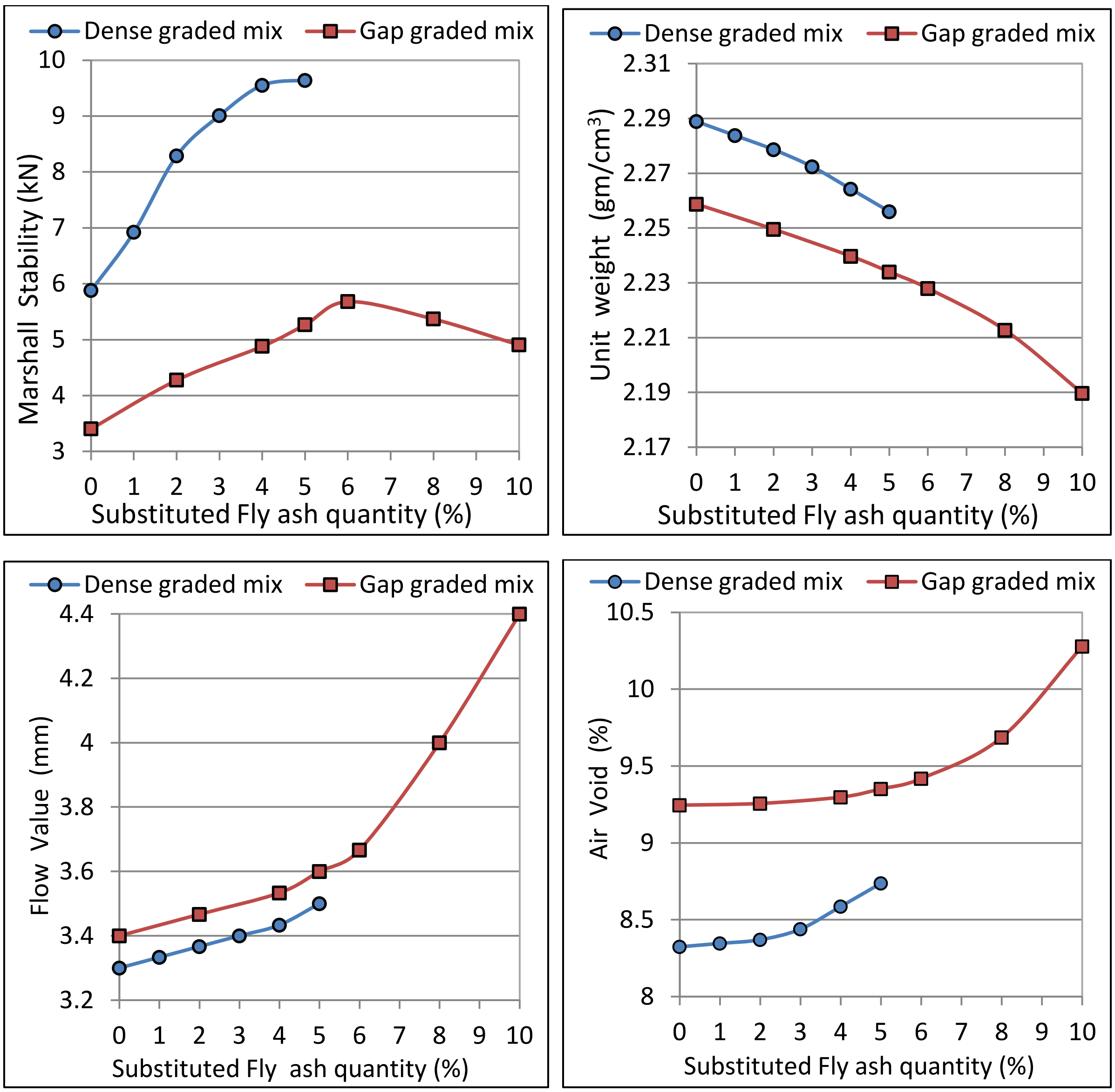

Figure 4.11 Marshall Stability, Unit weight, Flow value and Air void results of cold mixes modified with fly ash additive

From the above Marshall test results it was clearly observed that the dense graded cold mix performed superior than the gap graded cold mix in every aspect. It was also noticed that the adopted aggregate gradation could not meet the design air void requirement. Hence in next step further study was conducted to develop aggregate gradations by suitable adjustments in the initial aggregate gradations.

4.5 Effect of Developed Aggregate Gradation

Following nomenclature for the developed aggregate gradations was adopted for ease in frequent representation of mixes and they are summarised in table 4.6. Case 1 and Case 2 represent the minimum and maximum CA ratios and Case (a), Case (b) and Case (c) represent the middle, upper and lower limit of filler content respectively within the initial gradation limits. For example, Case (1a) represents developed aggregate gradation with the minimum CA ratio and middle limit of filler content.

Table 4.6 Nomenclature for developed aggregate gradations

Dense graded cold mix	Gap graded cold mix	Description
Cold Mix D	Cold Mix G	Cold mix with initial gradations
Cold Mix D(1a)	Cold Mix G(1a)	Cold mix with gradation with min. CA ratio and middle value of filler quantity
Cold Mix D(1b)	Cold Mix G(1b)	Cold mix with gradation having min. CA ratio and max. value of filler quantity
Cold Mix D(1c)	Cold Mix G(1c)	Cold mix with gradation having min. CA ratio and min. value of filler quantity
Cold Mix D(2a)	Cold Mix G(2a)	Cold mix with gradation having max. CA ratio and middle value of filler quantity
Cold Mix D(2b)	Cold Mix G(2b)	Cold mix with gradation having max. CA ratio and max. value of filler quantity
Cold Mix D(2c)	Cold Mix G(2c)	Cold mix with gradation having max. CA ratio and min. value of filler quantity

Note: D: Dense gradation G: Gap gradation Case (a): Middle value for filler content
Case 1: maximum CA ratios Case (b): Maximum filler content
Case 2: minimum CA ratios Case (c): Minimum filler content
All the values were taken within the initial gradation limits
Hence Case 1(b) presents gradation with maximum CA ratios and maximum filler content while Cold Mix D(1b) presents dense graded cold mix with above gradation.

The spreadsheet used in the present study is shown in figure 4.12. It was consructed for developing the aggregate gradations. Detailed method for gradation design and mix preparation was explained in section 3.5.

Sieve used	Original % passing by weight	Initial ratios	Original % retained	Initial % in blend by volume	Rodded unit weight (kg/m^3)	Loose unit weight (kg/m^3)	Bulk specific gravity	% of desired unit weight	Choosen unit weight (kg/m^3)	C.A. Contribution in mix (kg/m^3)	% of VCA	Total VCA (%)	F.A. contribution in mix (kg/m^3)	Unit weight for the aggregate blend (kg/m^3)	% of initial blend by weight of aggregate	Adjustment for filler	% passing by weight of aggregate	New ratios
NMPS	i/p				i/p	i/p							-				o/p	
	i/p				i/p	i/p							-				o/p	
HS	i/p	CA			i/p	i/p	i/p						-				o/p	CA
	i/p				i/p	i/p							-				o/p	
PCS	i/p				i/p	i/p							-				o/p	
	i/p				i/p	-				-	-	-					o/p	
SCS	i/p	FAc			i/p	-				-	-	-					o/p	
	i/p				i/p	-	-	100 % ruw		-	-	-					o/p	FAc
TCS	i/p	FAf			i/p	-				-	-	-					o/p	
	i/p				i/p	-				-	-	-					o/p	FAf
0.075 mm	i/p				i/p	-				-	-	-					o/p	
< 0.075	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	i/p	-	-

i/p : in put data   o/p : out put result   [ ] : value calculation   - : not applicable

Figure 4.12 Spread sheet for developing aggregate gradations

4.5.1 Dense graded cold mixes

The six numbers of developed aggregate gradations are shown in figure 4.13.

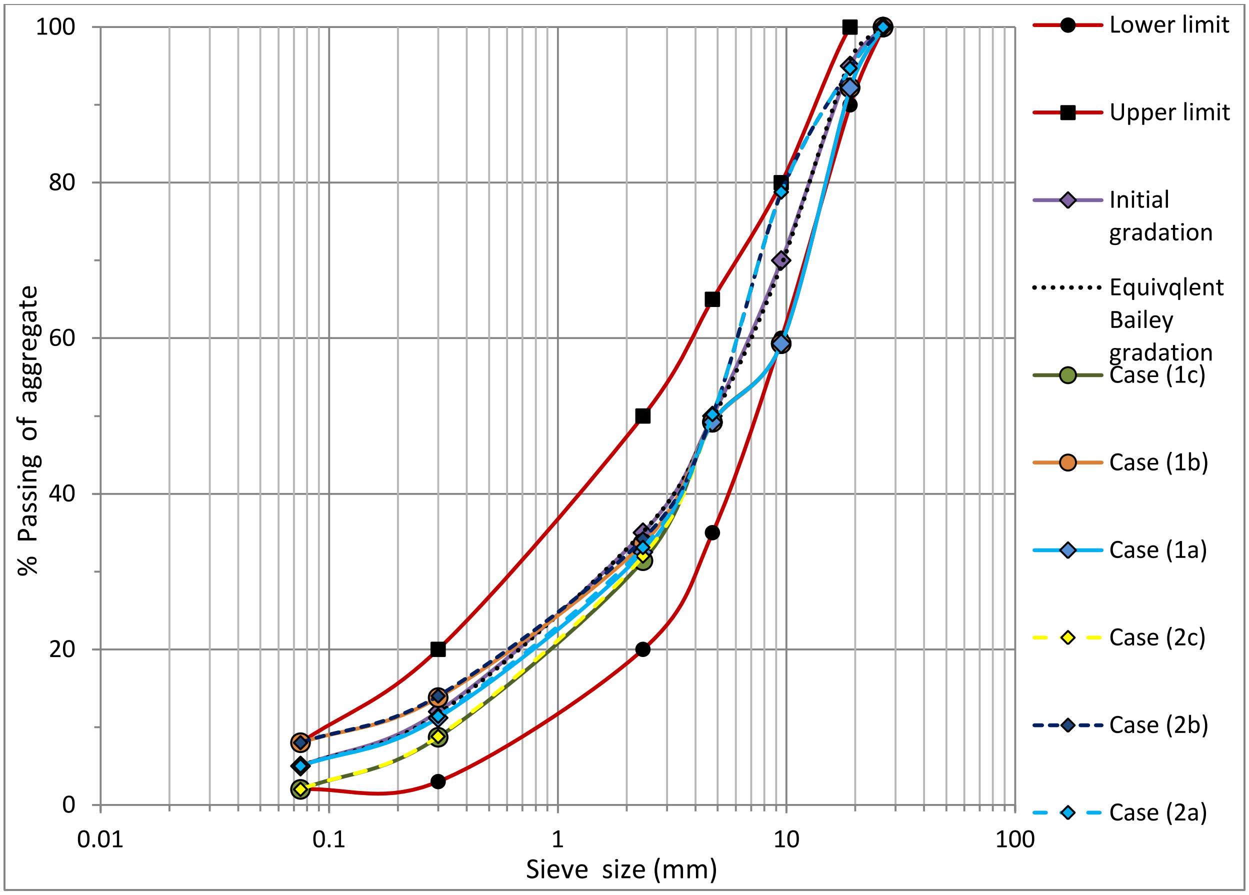

Figure 4.13 Developed aggregate gradations for dense graded cold mix (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

Marshall test results obtained for dense graded cold mixes are shown in figure 4.14 to 4.17.

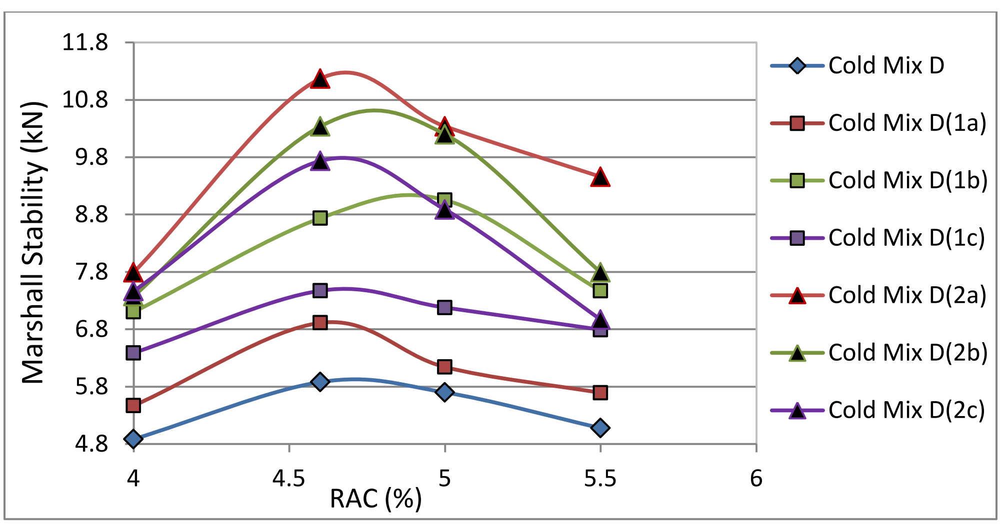

Figure 4.14 Marshall Stability results of developed dense graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

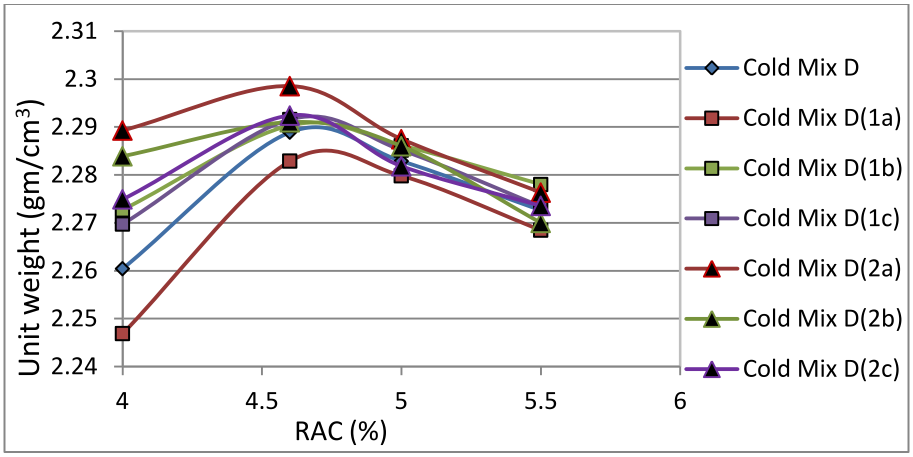

Figure 4.15 Unit weight results of developed dense graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

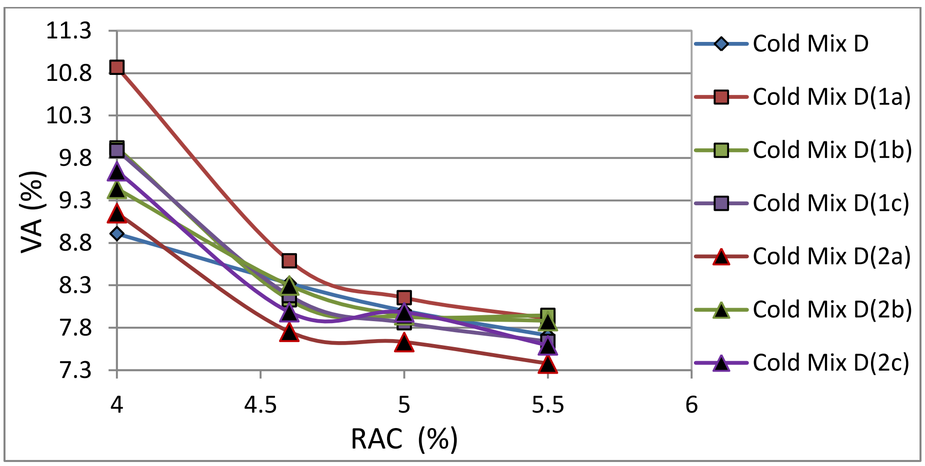

Figure 4.16 Air void results of developed dense graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

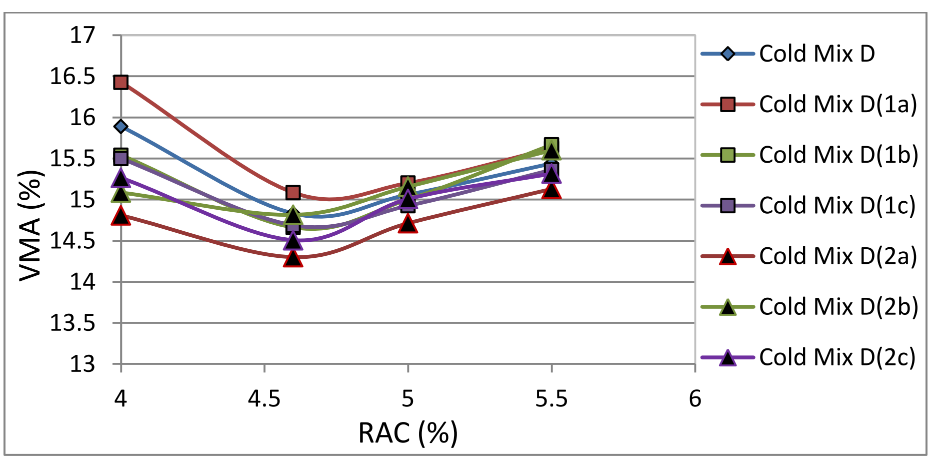

Figure 4.17 VMA results of developed dense graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

From the results shown above it was found that the Marshall Stability of all developed aggregate gradations was higher than the initial gradation and it was highest in case of Cold Mix D(2a) (gradation with maximum CA ratio and middle value of filler content). The flow value was found to be less sensitive and varied between a range of 2.2 to 2.3 mm for all gradations. But the air void and VMA results did not show any regular characteristics.

Two sets of cold mixes with initial gradations were compacted and undergone through 72 hours oven curing at 40^{o}C and 21 days curing at room temperature. Around eight percentage higher indirect tensile strength was observed in the later case. Then cold mixes compacted with initial gradation and six improved gradations were cured for 72 hours oven curing at 40^{o}C to perform the indirect tensile strength (ITS) test. From the ITS test it was observed that for all gradations, the ITS value decreased with increase in temperature. It was also observed that Cold Mix D(2a) (gradation with maximum CA ratio and middle value of filler content) had the highest indirect tensile strength. Figure 4.18 shows the variations of Indirect tensile strength (ITS) value with temperature for dense graded cold mixes including initial and six improved gradations.

From the static creep test it was observed that Cold Mix D(2a) (gradation with maximum CA ratio and middle value of filler content) had less deformation than the mix compacted with initial gradation. The obtained test results are shown in figure 4.19.

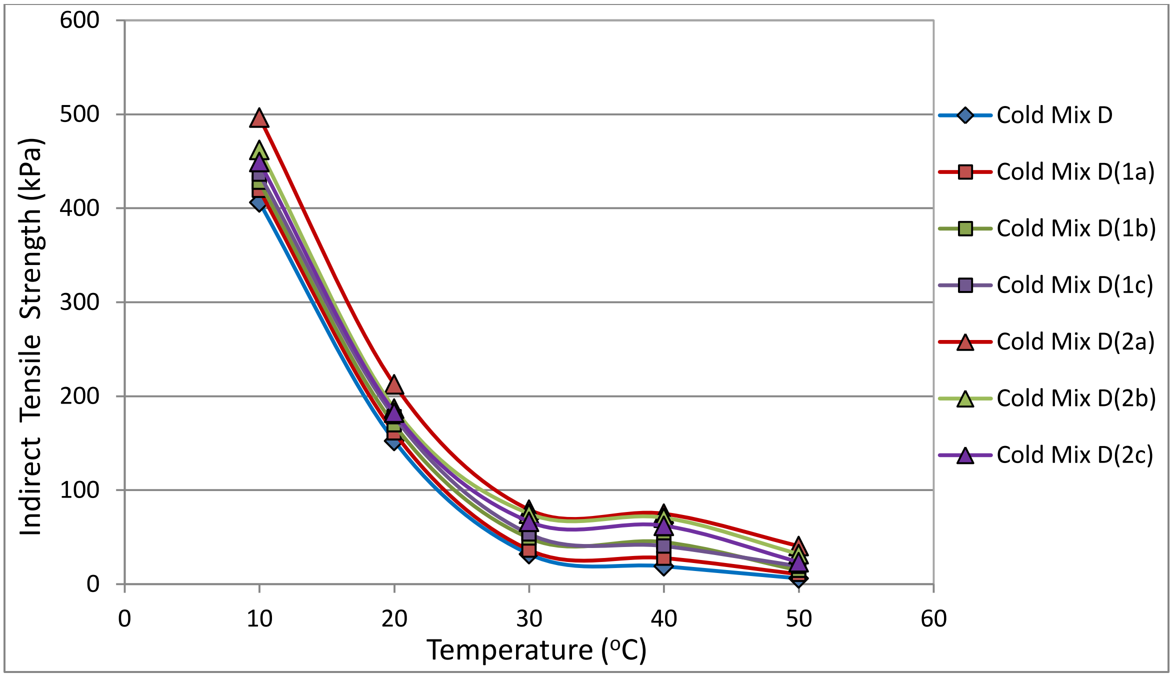

Figure 4.18 Variation of ITS Value of dense graded mixes with different temperatures (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

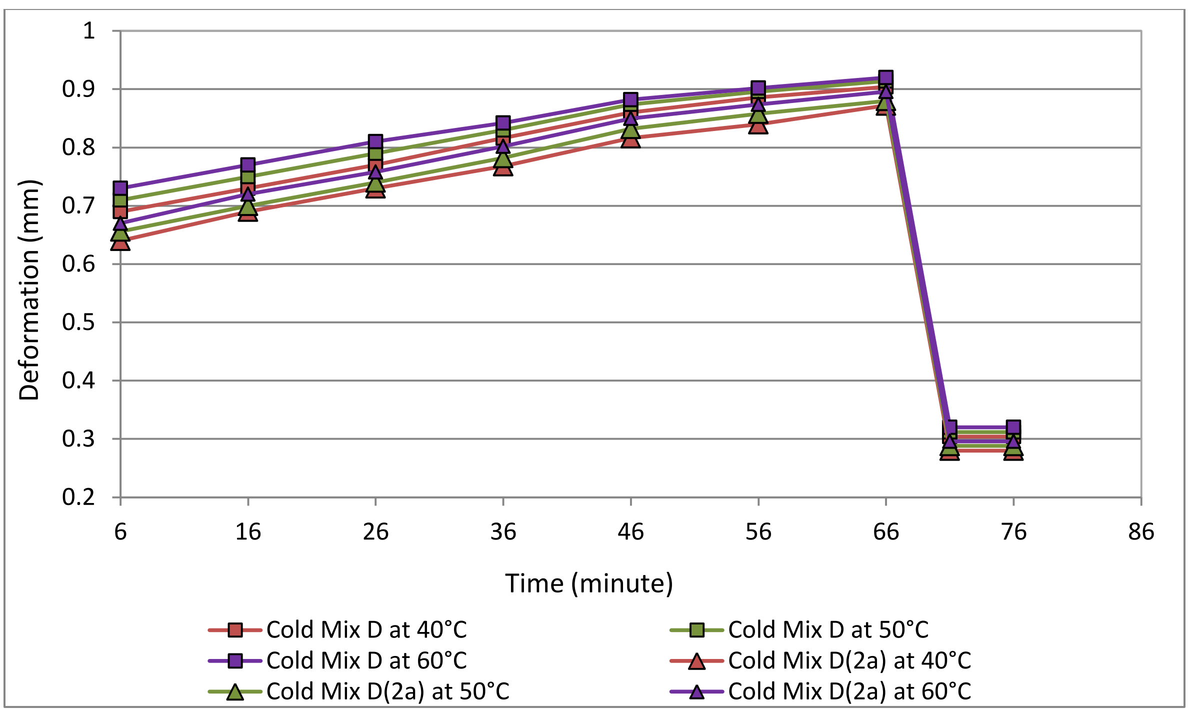

Figure 4.19 Deformation of dense graded mixes

(Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

4.5.2 Gap graded cold mixes

The six numbers of developed aggregate gradations are shown in figure 4.20. From the results shown it was found that the Marshall Stability of all developed aggregate gradations was higher than the initial gradation and it was highest in case of Cold Mix G(2c) (gradation with maximum CA ratio and minimum value of filler content). The flow value was found to be less sensitive and varied between a range of 2.3 to 2.5 mm for all developed gradations. But the air void and VMA results did not show any regular characteristics. Marshall test results obtained for gap graded cold mixes are shown in figure 4.21 to 4.24.

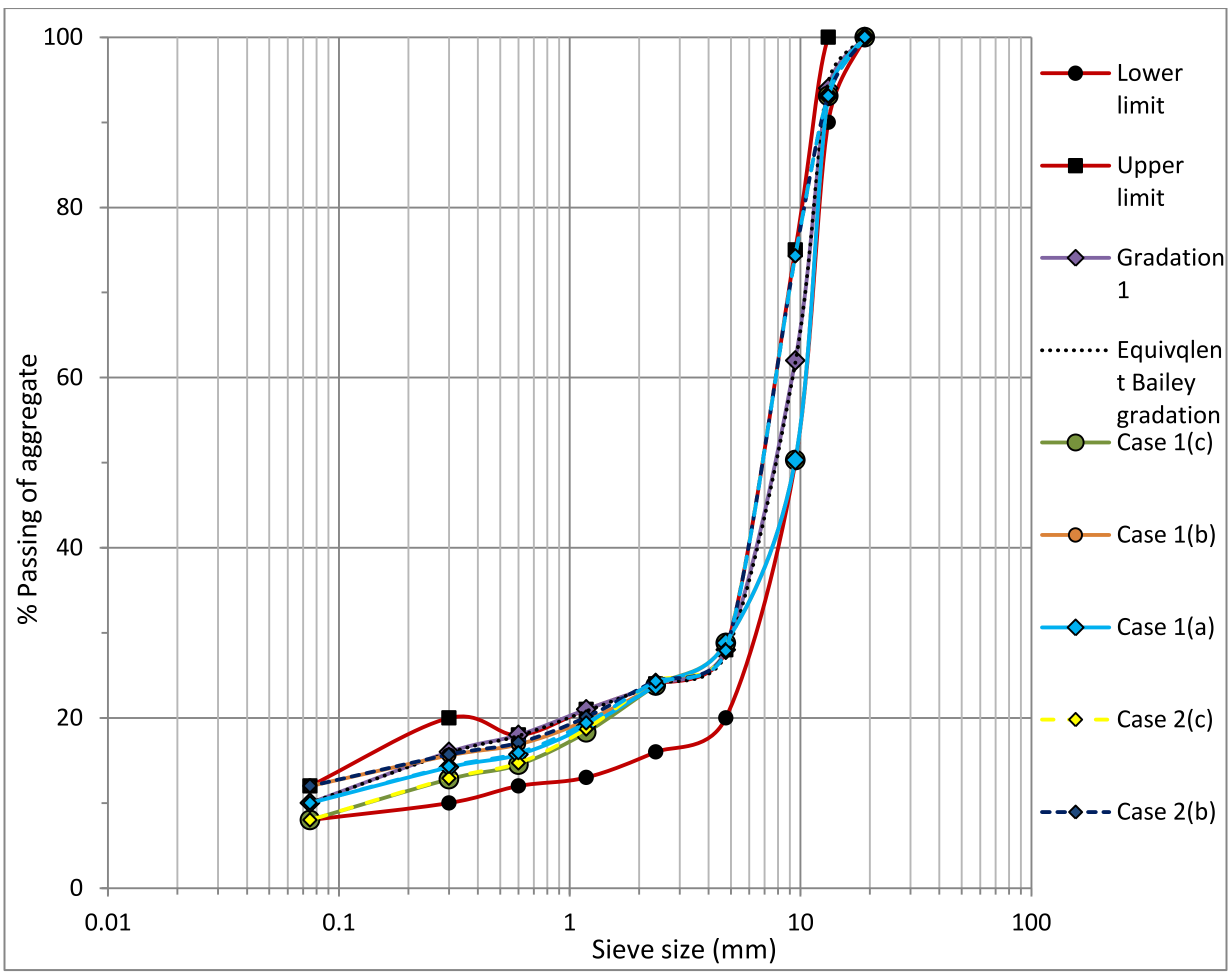

Figure 4.20 Developed aggregate gradations for gap graded cold mix
(Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

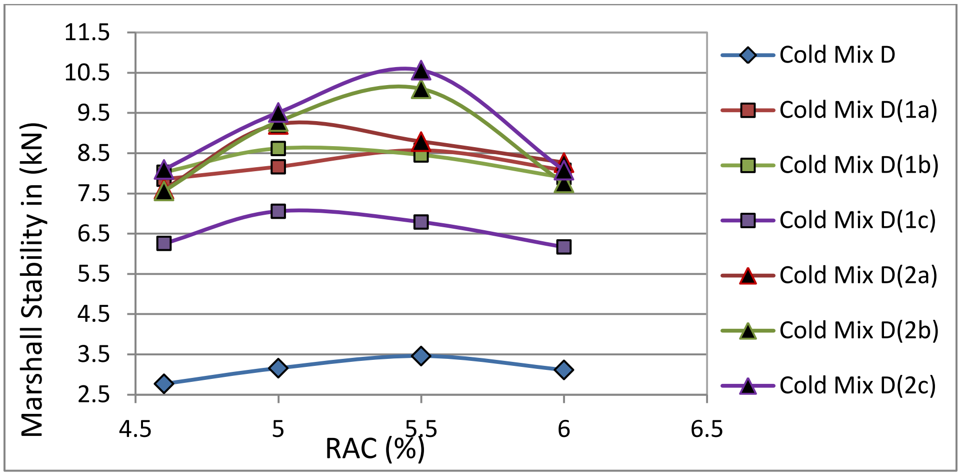

Figure 4.21 Marshall Stability results of developed gap graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

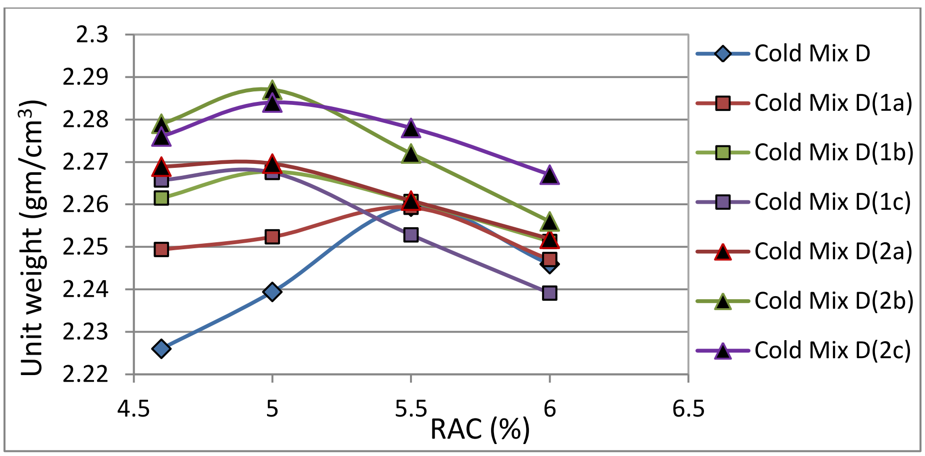

Figure 4.22 Unit weight results of developed gap graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

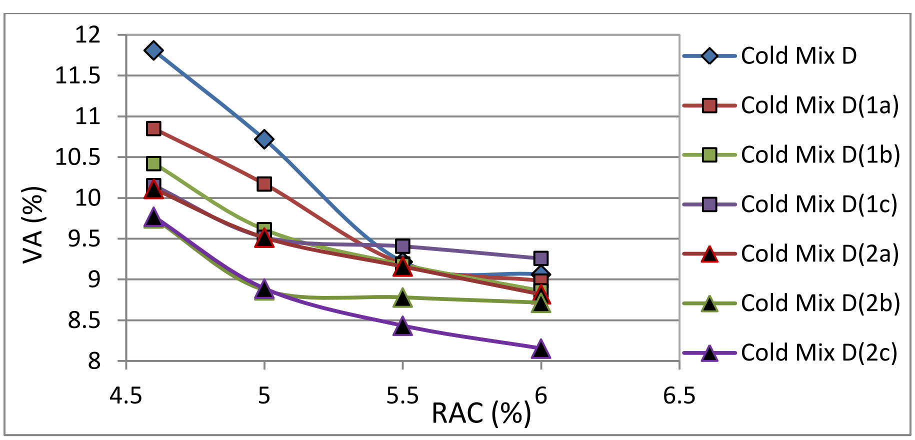

Figure 4.23 Air void results of developed gap graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

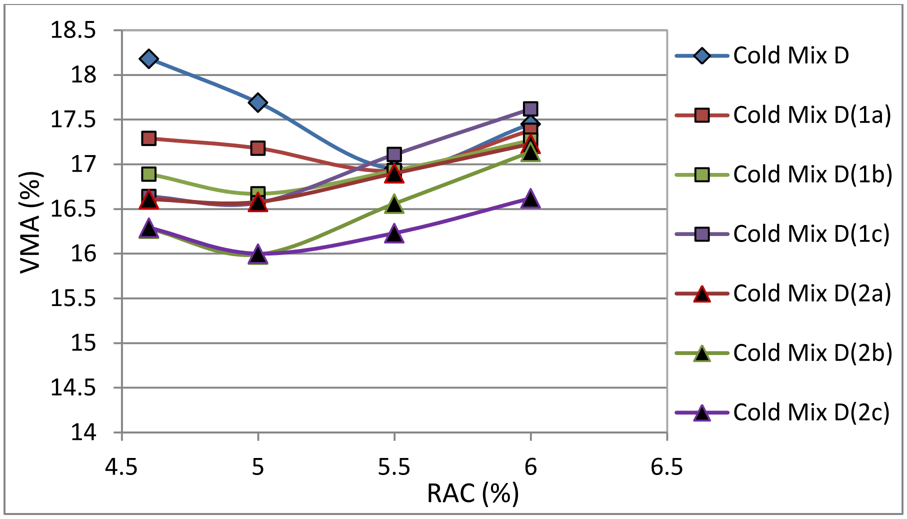

Figure 4.24 VMA results of developed gap graded mixes
(Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

In the similar way like the dense graded cold mixes, two sets of cold mixes with initial gradations were compacted and undergone through 72 hours oven curing at 40^{o}C and 21 days curing at room temperature. Around seven percentage higher indirect tensile strength was observed in the later case. Then cold mixes compacted with initial gradation and six improved gradations were cured for 72 hours oven curing at 40^{o}C to perform the indirect tensile strength (ITS) test. From the ITS test it was observed that for all gradations, the ITS value decreased with increase in temperature. It was also observed that Cold Mix G(2c) (gradation with maximum CA ratio and minimum value of filler content) had the highest indirect tensile strength. Figure 4.25 shows the variations of Indirect tensile strength (ITS) value with temperature for gap graded cold mixes including initial and six improved gradations.

From the static creep test it was observed that Cold Mix G(2c) (gradation with maximum CA ratio and minimum value of filler content) had less deformation than the mix compacted with initial gradation. The obtained test results are shown in figure 4.26.

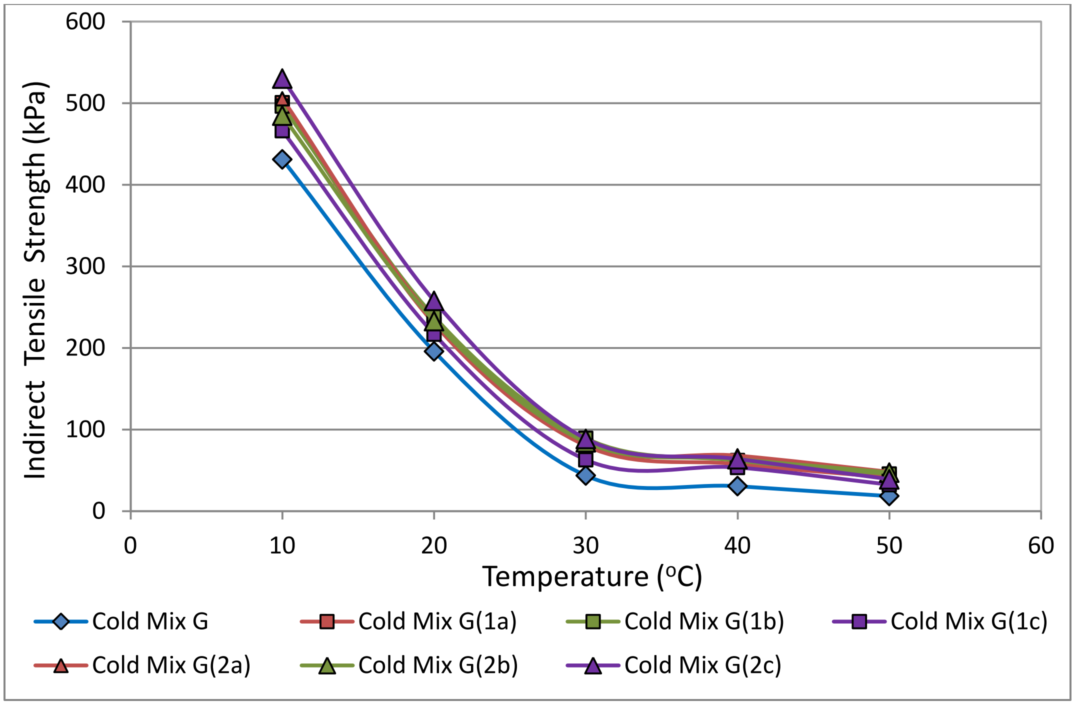

Figure 4.25 Variation of ITS Value of gap graded mixes with different temperatures (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

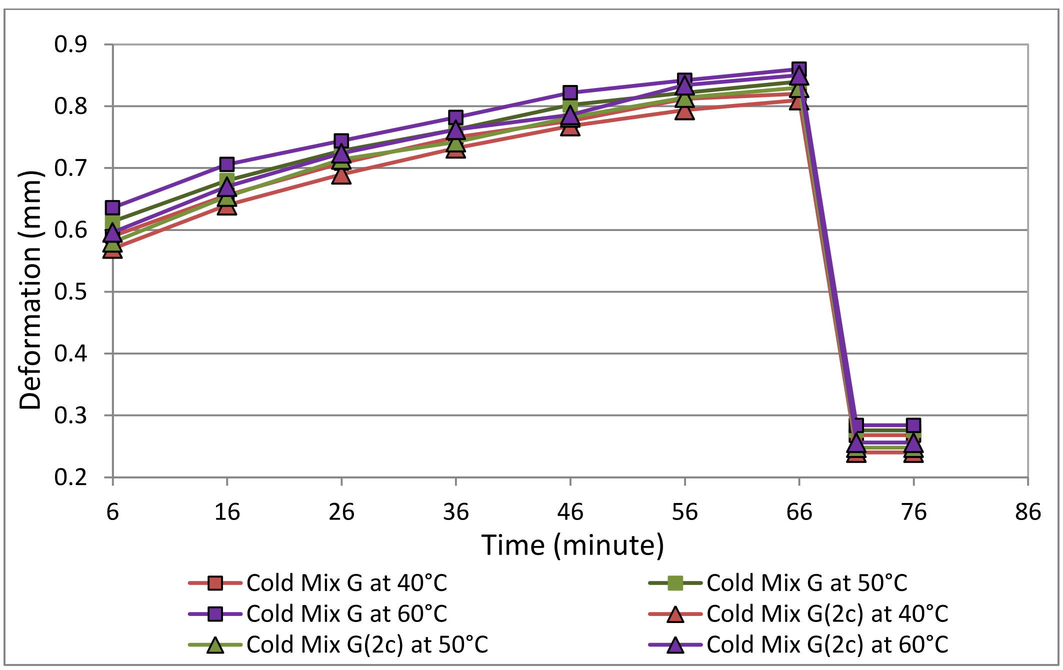

Figure 4.26 Deformation of gap graded mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

4.5.3 Comparative study between dense graded and gap graded cold mixes

The variations of Indirect tensile strength (ITS) value with temperature and deformation with time for both dense and gap graded cold mixes including initial and improved gradations are shown in figure 4.27 and figure 4.28 respectively.

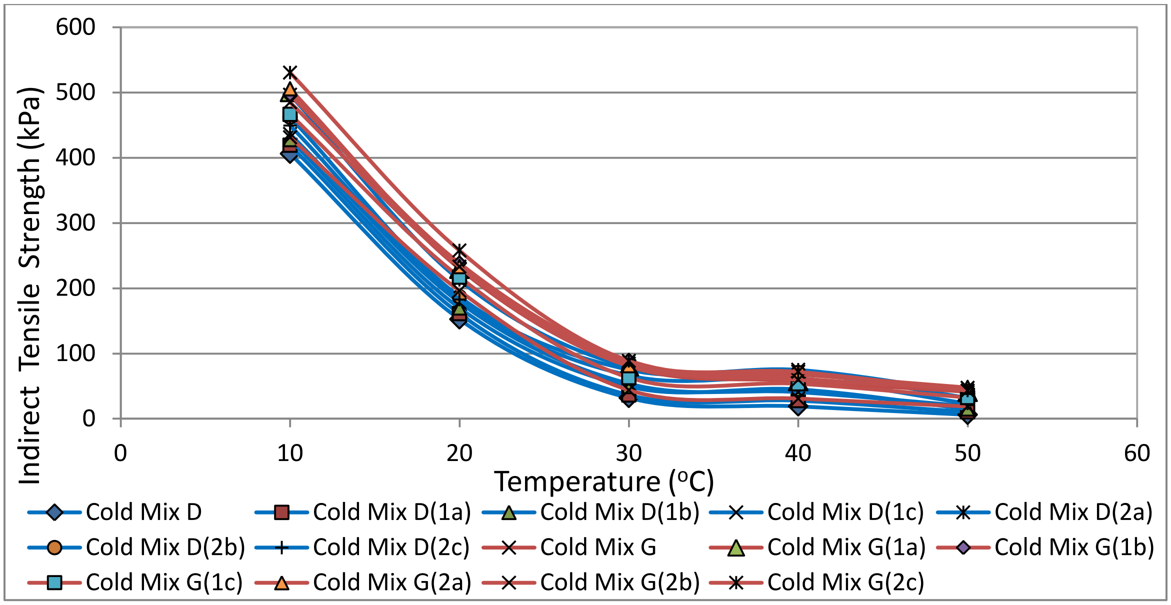

Figure 4.27 Comparative study for indirect tensile strength of cold mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

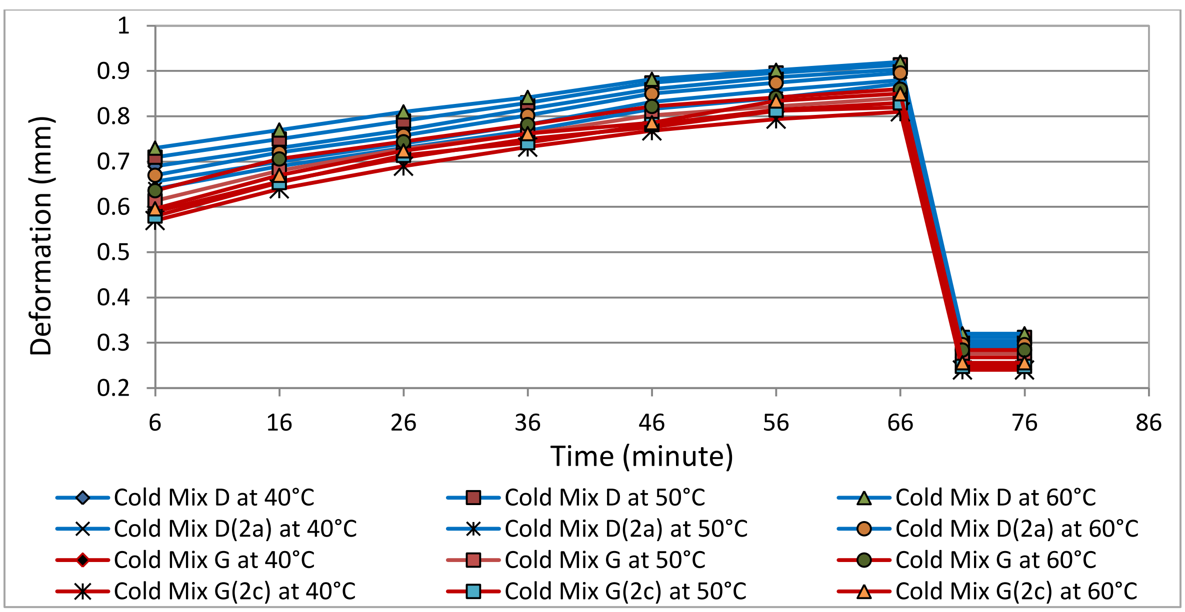

Figure 4.28 Comparative study for deformation of cold mixes (Refer table 4.6 in page no. 59 for adopted cold mix nomenclature)

From the above results it was noticed that higher indirect tensile strength and lesser deformation was obtained in case of gap graded mix in comparison to the dense graded mix.

4.6 Effect of Gyratory Compaction

Marshall compaction failed to achieve the design air void range. Hence the effect of gyratory compaction on air void content of cold mixes was studied.

4.6.1 Dense graded cold mix

Dense graded cold mixes were compacted with initial gradations given in table 3.2. The IRAC, IEC and OPWC value were 6 %, 9.17 % and 3 % respectively same as given in section 4.2.1 for Marshall compaction. Then tests were conducted to determine the number of gyration, OTLC and ORAC values following the design procedure provided in table 3.1.

- Determination of number of gyration:

Four numbers of gyration level (40, 80, 100 and 120 gyrations) were tried as per the preparation process explained in section 3.5 to check the minimum number of gyration required to achieve the lower limit of design air void (3 %). The obtained result is shown in figure 4.29.

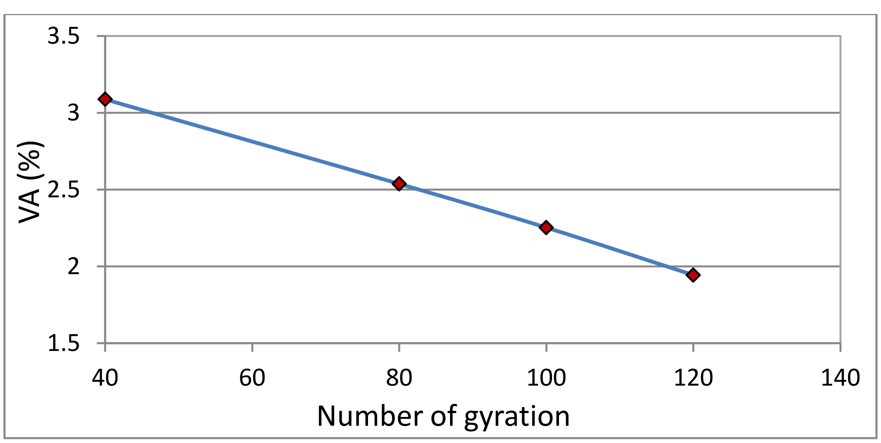

Figure 4.29 Selection of number of gyrations for dense graded cold mix

From the observation 40 gyration was selected for further study.

➢ Determination of OTLC value:

From the dry stability test result shown in figure 4.30 it was found that 5 % pre-wetting water content resulted the maximum dry density and the OTLC was determined as 7.07 %.

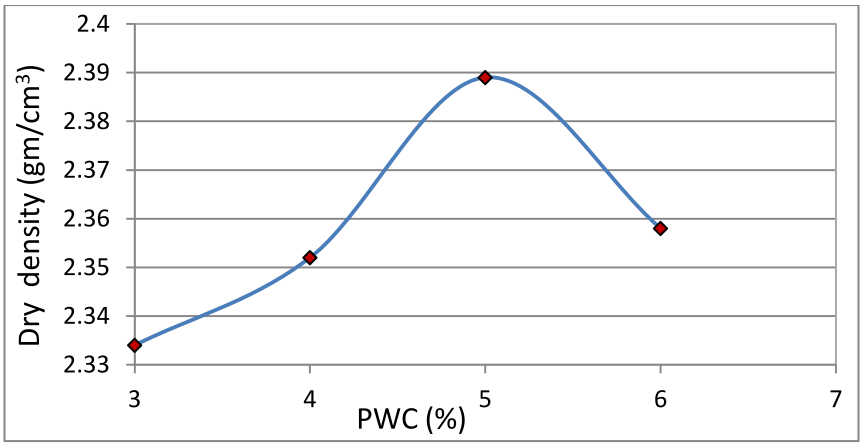

Figure 4.30 OTLC determination for dense graded cold mix in gyratory compaction

➢ Determination of ORAC value:

Maintaining the OTLC value found above RAC was varied. The obtained results for Marshall Stability and air void value are given in figure 4.31.

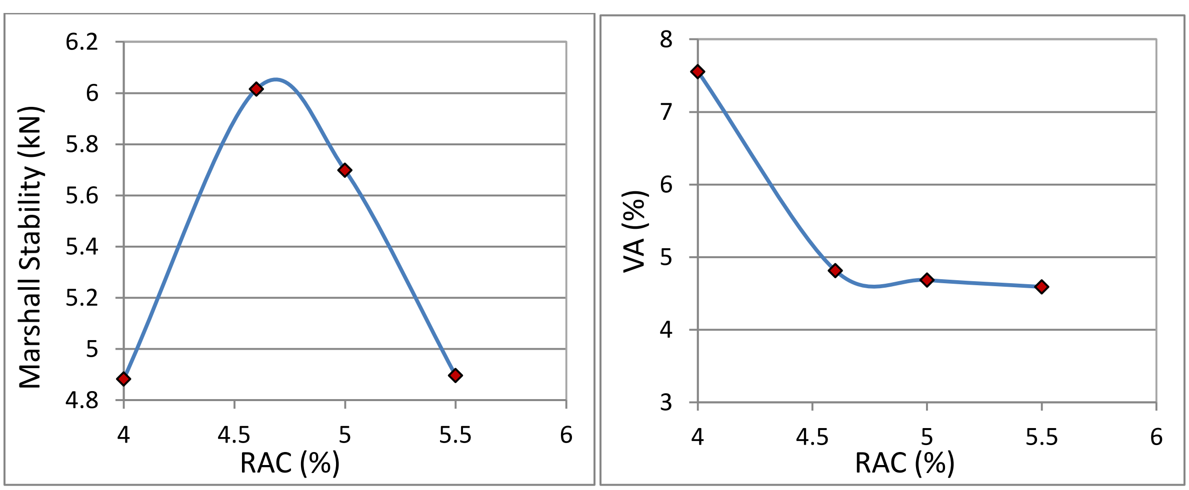

Figure 4.31 Marshall Stability and Air void results of dense graded cold mix in gyratory compaction

The maximum soaked stability was found at 4.6 % RAC. So, it was treated as ORAC and all other design parameters were also found to be adequate at ORAC.

4.6.2 Gap graded cold mix

Gap graded cold mixes were compacted with initial gradations given in table 3.3. The IRAC, IEC and OPWC value were 7 %, 10.7 % and 3 % respectively same as given in section 4.2.2 for Marshall compaction. Then tests were conducted to determine the number of gyration, OTLC and ORAC values following the design procedure provided in table 3.1.

- Determination of number of gyration:

Four numbers of gyration (40, 80, 100 and 120 gyrations) were tried as per the preparation process explained in section 3.5 to check the minimum number of gyration required to achieve the lower limit of design air void (3 %). The obtained result is shown in figure 4.32. From the observation 40 gyration was selected for further study.

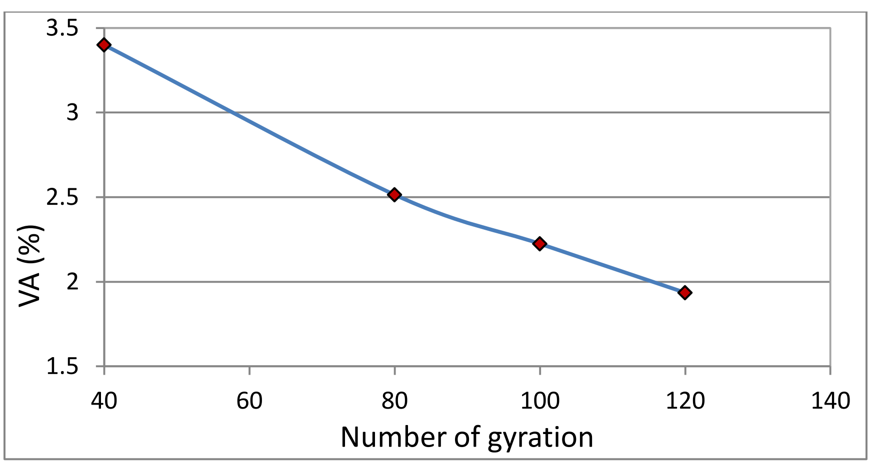

Figure 4.32 Selection of number of gyrations for gap graded cold mix

- Determination of OTLC value:

From the dry stability test result shown in figure 4.33 it was found that 5 % pre-wetting water content resulted the maximum dry density and the OTLC was determined as 7.07 %.

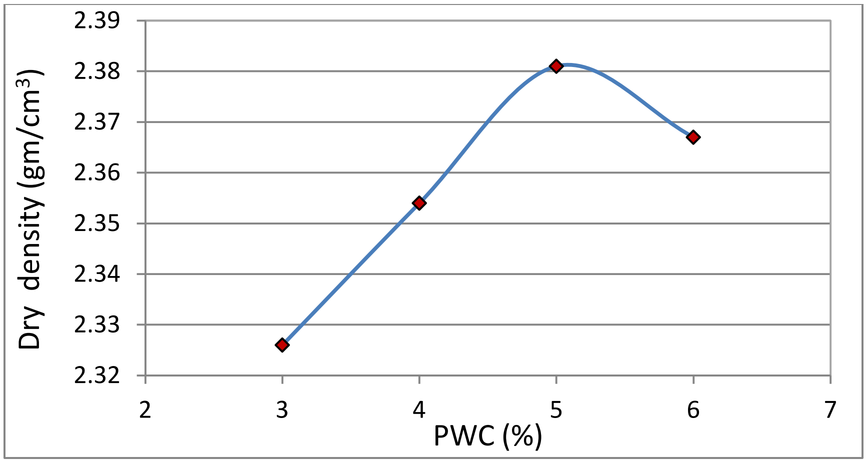

Figure 4.33 OTLC determination for gap graded cold mix in gyratory compaction

➢ Determination of ORAC value:

Maintaining the OTLC value found above RAC was varied. The obtained results for Marshall Stability and air void value are given in figure 4.34. The maximum soaked stability was found at 5.5 % RAC and it was treated as ORAC. All other design parameters were also found to be adequate at ORAC.

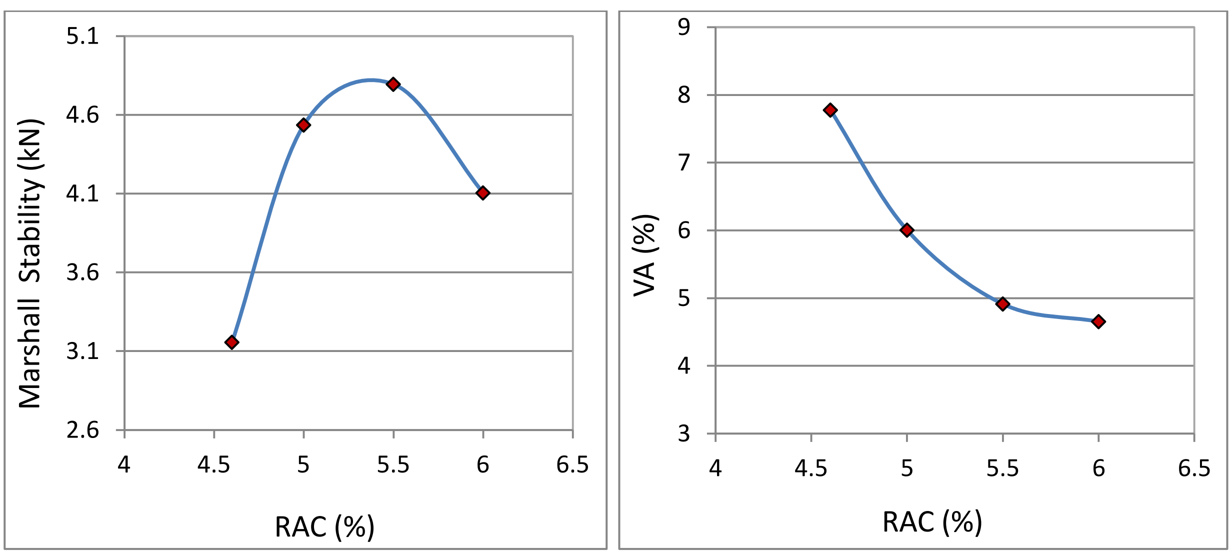

Figure 4.34 Marshall Stability and Air void results of gap graded cold mix in gyratory compaction

4.6.3 Comparative study between dense graded and gap graded cold mixes

The results obtained for Marshall Stability and air void for dense and gap graded cold mix in both method of compaction are summarised in table 4.7.

Table 4.7 Marshall Stability and air void results of cold mixes for Marshall and gyratory compaction

Marshall compaction (50 blows)		Gyratory compaction (40 gyrations)	
Dense graded mix	**Gap graded mix**	**Dense graded mix**	**Gap graded mix**
Marshall Stability = 5.88 kN	Marshall Stability = 3.46 kN	Marshall Stability = 6.02 kN	Marshall Stability = 4.54 kN
Air void = 8.32 %	Air void = 9.22 %	Air void = 4.82 %	Air void = 4.91 %

From the comparative study it was observed that though gyratory compaction method did not show much influence on the Marshall Stability but it was highly effective to reduce the air void content in cold mix asphalt and to get the adequate air void range (3 to 5 %) even at 40 numbers of gyration.

4.7 Effect of Mix Parameters on Cold Mix Asphalt Performance

The effect of mix parameters on Marshall Stability and percentage of air void in cold mixes are shown in figure 4.35 and figure 4.36 respectively.

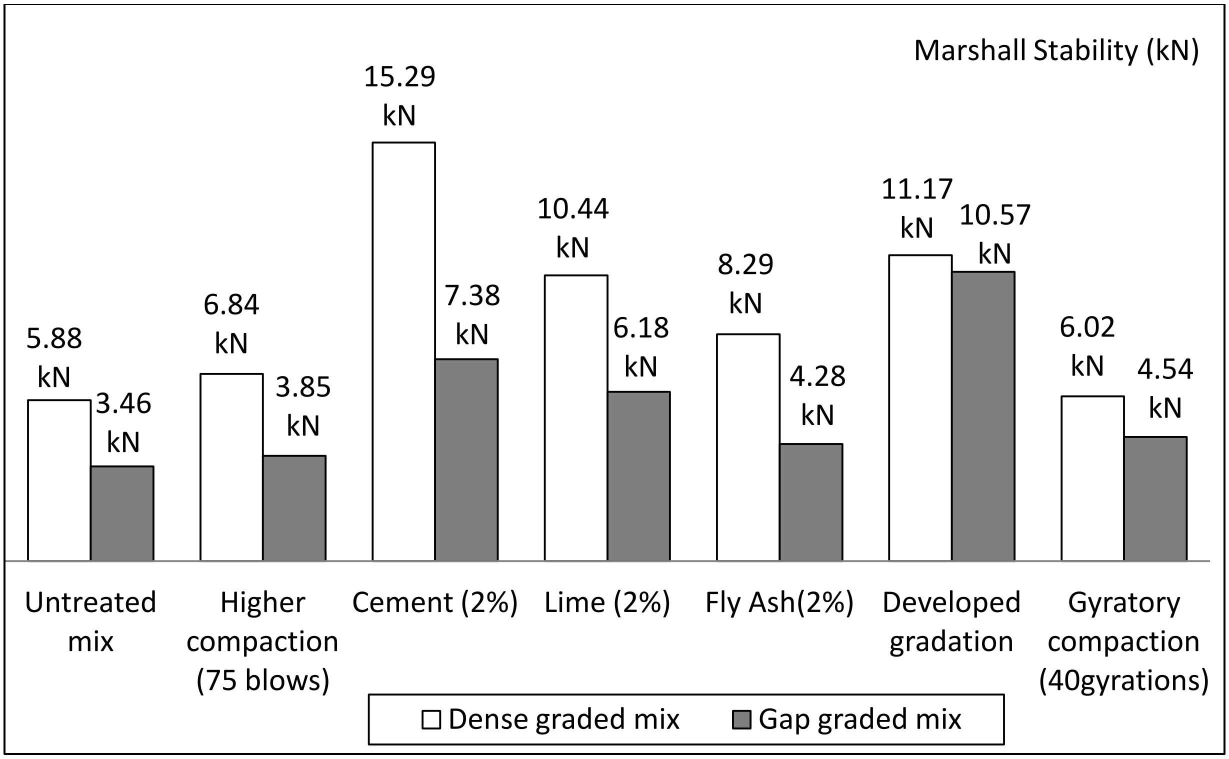

Figure 4.35 Effect of mix parameters on Marshall Stability of cold mixes

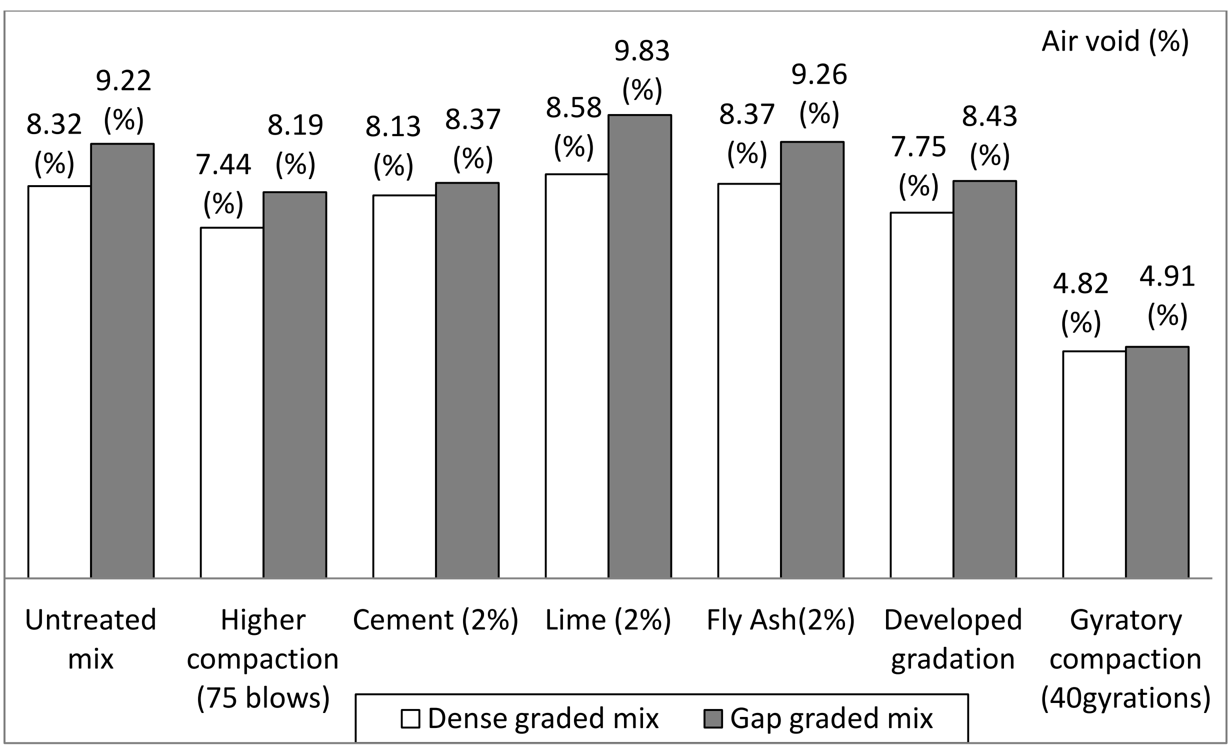

Figure 4.36 Effect of mix parameters on percentage of air void in cold mixes

4.8 Summary

In this chapter by using the adopted cold mix design procedure the effects of selected mix parameters on performance of CMA mixtures are studied. Finally a comparative study for above results has been done on basis of the Marshall Stability and air void content of the cold mix. Additive like cement is found to be highly effective as observed in the series of literature. In addition Bailey method is found to be effective in improving the Marshall Stability of cold mixes. It is also observed that the adequate air void range as specified by MORTH (2001) can be achieved by gyratory compacted cold mixes only.

Chapter five presents the summary and conclusions of the project work. It also gives the limitations of present work and recommendations for future research scope in this area.

Chapter 5

Summary, Conclusions and Recommendations

5.1 Summary

The lack of awareness in both research and application of cold mix technology, which is quite observable in India, is the primary motivation underlying selection of this research area for the present project work. The objectives of this project work are aimed to solve some present difficulties as well as to study the influence of aggregate gradation on performance of cold mix. Different mix parameters has been selected for the present work based on their importance and requirement.

From the review of literature, it has been found that the mechanical properties of the cold mix are affected by a number of parameters. Hence no universally accepted mix design procedure is available till now. The design procedure provided by Thanaya (2007) is found to be accepted by most of the researchers. It has been also found that Bailey method for gradation selection is the only method available which analyses the aggregate gradation considering both blend by volume as well as blend by weight.

After preparing a suitable experimental methodology, the effect of selected mix parameters on performance of compacted mix are studied. Finally a comparative study for above results has been done on basis of the Marshall Stability and air void content of the cold mix. Additive like cement, Bailey method for gradation design and gyratory compaction for cold mixes are found to show significant effect on performance of cold mix.

5.2 Conclusions

From the above study following conclusions are drawn based on performance of the cold mix.

- From the limited study it is observed that initial stability of the mix is dependent on optimum total liquid content (OTLC) of the compacted mix. At same binder content higher the total liquid content, greater is the curing time to obtain full strength of the mix. Although achieving OTLC is difficult for field application, it may be applied for laboratory procedures to avoid delay in work process. This concept has supported the adopted design procedure of the present study.
- Increment in the compaction level is found not to be much effective in decreasing the air voids in cold mixes rather it increased the stability loss value in the gap graded mix (SMA) which may be resulted due to the destruction of stone-to-stone contact skeleton at higher compaction level. Besides, higher is the compaction level, greater may be the difficulty in field applications.
- Increase in number of gyrations has resulted in the increased stability and reduced air void content of compacted cold mixes. 40 numbers of gyration has been found to be suitable as at higher level of compaction bleeding phenomenon of binder occurred which may affect the durability of the mix.
- Among the additives, though the stability value has been found to be improved by fly ash, lime and cement, performance of cement modified mix is observed to be superior in

every aspect. Comparing lime and fly ash as substituted for filler, greater stability but higher air void content is noticed in case of cold mixes modified with lime.

- The Bailey method for gradation selection has been found to be effective for improving the stability of both dense and gap graded cold mixes even without addition of cement.
- In between dense and gap graded cold mixes, though the dense graded mixes has resulted in higher stability value, it has showed lesser indirect tensile strength and higher deformation in comparison to gap graded mix.
- Considering all the selected mix parameters it is noticed that only in case of gyratory compaction the adequate air void range (3 to 5 %) in cold mixes has been achieved. Besides, though each and every parameter has contributed to increase the Marshall Stability of cold mixes, cement and developed gradations has shown more significant effect to increase the stability of cold mixes.

5.3 Limitations and Recommendations for Future Research

Some limitations of the present study and future scope in this area were sighted below.

- This study has been limited to the design procedures followed by MS 14 and few other researchers. So, other suitable procedures should be developed.
- The performance study of cold mix is primarily based on analysis of Marshall Stability and air void content in the compacted cold mix. The mix performance characteristics in terms of many other engineering properties need to be considered.

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